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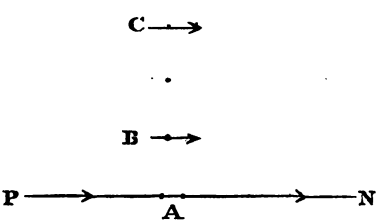
whether this velocity varies in different cases, nor have we any distinct idea of the causes that are likely to produce such variation. We can perceive, however, that the mode of transmission has a considerable influence on the results. The currents transmitted by perfect conductors are *continuous;* that is, their intensity is either constant, or varies insensibly during two consecutive instants. When the conductors are imperfect, the currents are *discontinuous;* for the electricity is allowed to accumulate for a certain time, and until the insulating force is overcome, when it escapes, and passes on with a sudden impulse, analogous to an explosion. The electro-motive power continuing to act, gives rise to a second accumulation, and a fresh explosion, and so on successively. These alternations may become sufficiently rapid to escape our senses, and thus produce the appearance of an uninterrupted current, although it be really discontinuous. The distinctive character of such currents is, that they are incapable of producing a deviation in the magnetic needle. This is the case with the current produced by the common electrical machine, when a communication is established between its positive and negative conductors: and also with the currents established in what have been called the *secondary piles* of Ritter (see *Electricity*, § 93), or piles constructed with a series of metallic discs separated by humid conductors. Discharges from the Leyden vial, in like manner, although they induce a degree of permanent magnetism in steel bars near which they pass, yet scarcely leave any traces of their effects on the needle of the galvanometer, when transmitted through the wires of that instrument.

(177.) The continuity of the electric current being the quality most immediately concerned in the production of the effects that are the subject of our present consideration; and it being impossible for us to discriminate differences of velocity or of quantity, in any other manner than by the total effects that result from the passage of the current through a conducting body, we shall distinguish continuous currents only in respect to their *intensity*, and pretend to judge of the degrees of intensity solely by the amount of the effects produced on the galvanometer.

(178.) In order to arrive at the fundamental law of electro-dynamic action of currents upon one another, it is necessary to consider the total action of each as resulting from the combined actions of every one of its parts. As it is not possible to institute a direct measurement of those elementary forces exerted by each indefinitely small portion, the one upon the other, the inquiry can only be made by assuming some hypothesis relative to the law of diminution according to distance, and prosecuting the consequences of such an hypothesis, when applied to such finite portions of current as occur in our experiments, and to compare them with actual observation, their accordance with which will be a test of the admissibility of the hypothesis.

(179.) Guided by the analogy of all the other known forces in nature, we shall assume that the mutual actions of the elementary portions of electric currents are inversely as the squares of their relative distances; and this is, in fact, the supposition which agrees best with all the facts that have hitherto been ascertained. If we suppose A, for instance (*fig.* 97), to be an indefinitely small portion of the rectilineal current P N, moving from left to right, it will act upon another elementary portion, B,

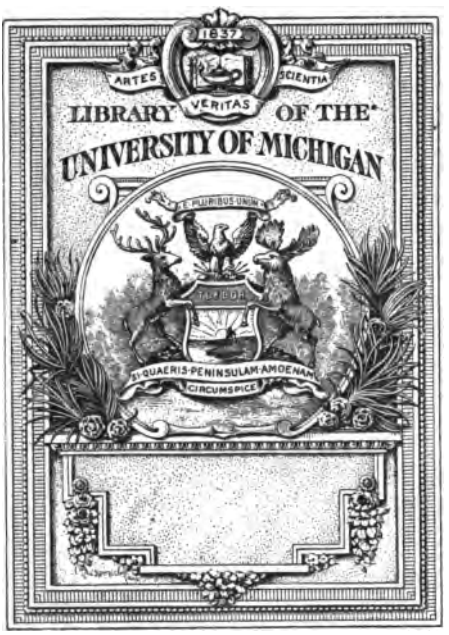
Fig. 97.



of a current placed at a given distance with nine times the energy that it exerts upon a similar portion of current placed at C three times further removed from it. If we call the force of attraction f the intensity of the first current a, and of the second current b, and the distance between them, or the line B A, d, the following equation will express the law just enunciated:—

$$f = \frac{a\ b}{d^2}$$

(180.) It may be demonstrated mathematically, that such being the law of elementary action, it will follow as a necessary consequence that the total



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TREATISES

ON

ELECTRICITY, GALVANISM,

MAGNETISM,

AND

ELECTRO-MAGNETISM.

BY

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PREFACE.

THE design of the present work is to offer a condensed and methodical Treatise on that important department of Natural Philosophy which comprises the diversified phenomena of Electricity and Magnetism. These phenomena, which were formerly regarded as the effects of two perfectly distinct agents, are now discovered to have an intimate relation to one another, and, in all probability, to be dependent on one and the same principle: in like manner as it was found by Newton, that the simpler mechanical phenomena of the universe are the results of the single principle of gravitation. A succinct and connected account of the numerous discoveries which the exertions of philosophers have recently brought to light on this highly interesting branch of physical science, collected from the various scientific Journals and Transactions through which they are dispersed, and digested in a didactic order, seemed to be particularly wanting, and to be especially calculated to further the objects of the *Society for the Diffusion of Useful Knowledge.* In pursuance of this design, I have aimed at giving to the subjects treated as much condensation as was compatible with perspicuity. I have endeavoured to conduct the student, by a regular progression, from the simpler to the more complex topics of research; and I have also been anxious, by placing constantly before his view the distinction which exists between ascertained facts, and the hypotheses and theories devised for their explanation, to illustrate the precepts of Bacon by examples, and to foster that genuine spirit of philosophical inquiry by which alone error can be avoided and truth attained.

For the many deficiencies which I fear the reader will discover in the completion of this design, I have to plead, in extenuation, the very scanty portion of leisure which the continual pressure of my professional duties leaves at my disposal. When I undertook this task, at the request of the Society, above four years ago, I was far from anticipating the extent of the labour it has imposed upon me; and from the multiplied interruptions to which I have been subject, I have been compelled to prosecute the work in a desultory manner, and at irregular and uncertain intervals.

Since the publication of the earlier Treatises composing this volume, many

valuable researches have been made, both in Electricity and in Galvanism, which deserve to be recorded in their proper places. This, however, is an inconvenience which, in the present age of improvement, must be incident to every scientific Treatise; for while so many accessions are daily accruing to the stock of information, it is hardly possible to keep pace with the rapid growth of knowledge; nor can we ever hope to incorporate the whole of the discoveries, which have been made up to the last moment of publication, in a systematic work on any science. To wait till perfection is attained would be vain and fruitless presumption; for the architecture of science has this peculiarity, that the foundations must be prepared, and the superstructure begun, long before the plans and elevations are completed. To posterity will be left the task of adding the key-stone, and of removing the scaffolding which interrupts the symmetry of the perfect edifice.

P. M. ROGET.

39, *Bernard Street, Russell Square,*
December 12, 1831.

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ELECTRICITY.

Chapter I.

General Facts and Principles.

(1.) The science of Electricity, which now ranks as one of the most important branches of Natural Philosophy, and which embraces so many subjects of inquiry, exceedingly curious in themselves, and highly interesting from their relations with every department of nature, is wholly of modern creation. The ancients were, indeed, acquainted with a few detached facts, depending on the agency of electricity; such as the attractive power which amber acquires by being rubbed, the benumbing shocks which are experienced on touching the *torpedo* (or electrical eel), and the appearance of those sparks or streams of light which, on some occasions, are seen to issue from the human body. But no suspicion was entertained that these phenomena had any connexion with one another; and far less was it imagined that they were the effects of a power pervading all material bodies, and extensively concerned in all the operations of nature.

(2.) It was only by slow degrees that this knowledge was acquired. The first step towards a generalization of the phenomena was made by Dr. Gilbert, an English physician, who, in the year 1600, published a very original and valuable treatise on the magnet. He remarked that several other bodies besides amber can, by friction, be made to attract light bodies; and he was thus led to the discovery of a property common to all of them. The Greek name for amber being ἤλεκτρον (*Electron*), the bodies possessed of this property were denominated *Electrics;* and the power they manifested was termed Electricity. The observations of Boyle, Otto Guericke, Newton, and a few other philosophers of the same period, contributed somewhat to the extension of our knowledge on this curious subject; but even the information collected during the whole of that century amounted to nothing that could be entitled to the name of science. The real science of Electricity can, properly speaking, be considered as taking its rise only in a later age; and it was the first fruit of that active spirit of investigation, which at the commencement of the eighteenth century was rapidly diffusing itself over Europe. The establishment of the Royal Society of London appears to have had considerable influence in promoting the cultivation of electricity: for we find that almost every discovery of importance in this science was made by the members, and is recorded in the Transactions of that Society. But it was not until the present century that the extensive relations which connect electricity with so many other branches of physical science, were discovered, and their importance appreciated. Already have we seen, in this short era, the rise of a new science, founded on that peculiar modification of Electricity, which is known by the name of Galvanism. Hence, have we derived new instruments of analysis, new paths of research, and new powers of extending the dominions of science; hence, have we been able to trace alliances between several of the great agents concerned in the phenomena of the material universe. Electro-Chemistry has thus arisen as one of the connecting branches between remote divisions of the Philosophy of Nature. Still more recently there has been opened to us, in the subject of Electro-Magnetism, another new province of science, which establishes a natural connexion between two powers hitherto regarded as distinct.

So rapid has been the march of scientific improvement, that it is difficult for those whose attention has not been steadily and exclusively devoted to these particular objects, to keep pace with the progress of discovery. The materials collected by the numerous labourers in these wide fields of inquiry have poured in upon us so fast, that there has scarcely yet been time for marshalling them in their proper places, and for

disposing them in the order best fitted for instruction. It is to be lamented that there exists as yet no general and comprehensive treatise embracing the whole of these extensive and complicated subjects of modern research; and that the student has still to gather the information he seeks from a multitude of journals and other miscellaneous sources, where they lie irregularly scattered, and are not to be arranged, or even found, without a great expenditure of time and labour. It is the aim of these treatises to supply, in some degree, this deficiency, in as far, at least, as relates to the instruction of those who have no previous acquaintance with the subject, and are desirous of being initiated in the principles of the science.

(3.) In order to convey the clearest and most philosophical views of the subject we are about to treat, we shall begin by stating, independently of all theory, the most general facts relating to Electricity; presenting them at first in their simplest form. We shall, in the second place, review the theories which have been framed for the purpose of connecting these facts in the mind. We shall thus be enabled, lastly, to study their combinations, to unravel their complicated results, and to follow them in their practical applications.

(4.) The general facts relating to Electricity may be reduced to the six following heads:—

1. Excitation.
2. Attraction.
3. Repulsion.
4. Distribution.
5. Induction.
6. Transference.

§ 1. *Of Excitation, Attraction, and Repulsion.*

(5.) If a piece of amber, or sealing-wax, or a smooth surface of glass, perfectly clean and dry, be briskly rubbed with a dry woollen cloth, and immediately afterwards held over small and light bodies, such as pieces of paper, thread, cork, straw, feathers, or fragments of gold leaf, strewed upon a table, these bodies will be seen to fly towards the surface that has been rubbed, and adhere to it for a certain time. The surfaces which have acquired by friction this attractive power are said to be *excited;* and the substances thus susceptible of excitation are termed *electrics*, in contradistinction to such as are not excitable by a similar process, and which are, therefore, termed *non-electrics.*

(6.) The principal electric substances in nature are the following: viz. amber, gum-lac, resin, sulphur, glass, talc, the precious stones, silk, the fur of most quadrupeds, and almost all vegetable substances (excepting charcoal), which have been thoroughly deprived of moisture, as, for example, baked wood, and very dry paper.

(7.) After the bodies which had been attracted by the excited electric have remained in contact with it a certain time, the force which held them together ceases to operate: the bodies then recede from the electric, and if the latter be again presented to them, they will, provided they have touched no other body, be repelled, or driven off, instead of attracted. This change from attraction to repulsion takes place more slowly with some substances than with others: some bodies will adhere to the electric a considerable time before they recede; while others, and especially metallic bodies, are repelled the instant after contact:—the reason of this will afterwards be seen.

(8.) It is also to be noticed that two bodies which have both of them been in contact with the same electric, mutually repel each other.

(9.) The phenomena of electrical attraction and repulsion are best observed when electrics of considerable size are employed. For the experiments we are about to describe, it is convenient to have them of a cylindrical shape, which admits of their being more easily carried in the hand, and more readily transferred to wherever we may wish to place them. We may employ as our electric a thick cylinder of sealing wax, or one of sulphur. If glass be chosen, it should be in the form of a tube of considerable diameter, and should, previously to the experiment, be gently warmed before the fire, in order to expel all moisture from its surface. As a rubber we may use a silk handkerchief, a piece of clean flannel, or the fur of a quadruped; but the material which produces the greatest effect when rubbed with glass is an amalgam (or mixture) of mercury with tin or zinc. Whatever be the substance employed, it should be perfectly dry; to ensure which condition it should, previously to being used, be held for some time before the fire.

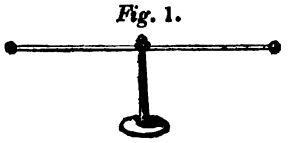
(10.) When, by attending to these precautions, a sufficiently powerful excite-

ment of the cylinder has been obtained, we may observe several other remarkable phenomena, besides those of attraction. If the experiment be performed in a dark room, flashes of light, of a bluish colour, will be perceived during the friction, extending over every part of the surface rubbed; and sparks, attended with a sharp snapping sound, will be seen to dart around it in various directions. If a round body, as a metallic ball, be presented to it, and moved from one end to the other, a succession of sparks will be obtained as the ball passes along the surface; and if the knuckle be presented instead of the metallic ball, each spark will be accompanied by a pricking sensation. When the excited cylinder is brought near to the face, an unpleasant sensation of tickling is felt in the skin, as if it had been covered with a cobweb.

(11.) If a globe of metal be suspended in the air by silk threads, and if, while in this situation, it be rubbed by an electric, such as silk, fur, or the outside of the skin of a cat, it will also become electrical, and exhibit the same properties of attraction and of repulsion as if it had been itself an electric. The circumstance of its being thus insulated or cut off from the contact of any substance, except the air and the electric which sustains it, is essential to the success of this experiment.

(12.) Various modes have been devised for exhibiting distinctly the attractive and repulsive agencies of electricity; and for obtaining indications of its presence, when it exists only in a feeble degree. Instruments for this purpose are termed *Electroscopes*. One of the simplest of these is the Electroscope of Haüy, which is very similar to that formerly proposed by Dr. Gilbert. It consists of a light metallic needle, terminated at each end by a light pith ball, which is covered with gold leaf,

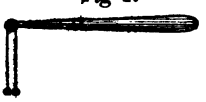
Fig. 1.



and supported horizontally by a cap at its centre, on a fine point. The attractive or repulsive power of any electrified body presented to one of the balls, will be indicated by the movements of the needle.

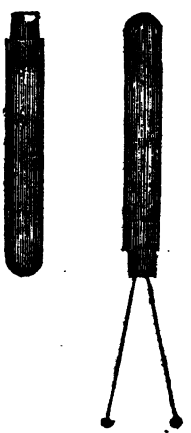
(13.) In some cases it is more convenient to employ a pair of similar balls, suspended from a brass ball fixed to the end of a glass handle, by very fine silver wires, or by hempen threads, previously steeped in a solution of salt, and afterwards dried. See *fig.* 2.

Fig 2.



(14.) Cavallo has contrived an electroscope of the same kind, which has the advantage of being more portable than that of Haüy, while it is, perhaps, equally sensible. It is formed by two fine silver wires, each carrying at one of their ends a little ball made of cork, or of the pith of the elder tree; the other ends of the wires being suspended from a cork, which is rather long, and tapering at both ends, so as to fit either way into the mouth of a varnished glass tube, serving both as a handle to the instrument when in use, and as a case for it when carried in the pocket. When it is to be employed as an electroscope, the wires with pith balls are placed so as to hang out from the end of the tube, and will indicate by their divergence any electricity which may be communicated to them. (*Fig.* 4.) When

Fig. 3. *Fig.* 4.

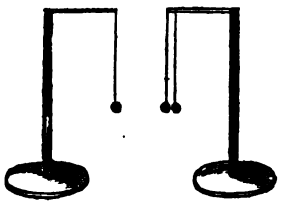


the instrument is not in use, the wires are put into the tube, by inverting it, and closing it with the other end of the cork. (*Fig.* 3.)

(15.) For studying the circumstances

attending electrical attraction, we should be provided with stands, from the ends of which are suspended by their respec-

Fig 5.

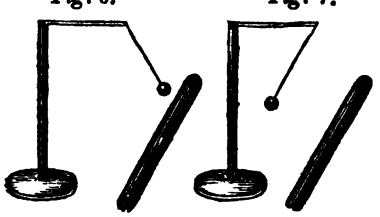


tive threads one or two pith balls, about the size of a small pea, as shown in *fig.* 5.

§ 2. *Distribution and Transference.*

(16.) If an excited electric be brought near a pith ball suspended by silk, the ball will, in the first place, approach the electric (*fig.* 6.), indicating an attraction towards it, and if the position of the electric will allow, the ball will come into contact with it and adhere to it for a short time; but it will presently afterwards recede from the electric, showing that it is now repelled. (*fig.* 7.) If we

Fig. 6. *Fig.* 7.



now remove the electric, and present to the ball which has thus touched it, a second ball which has had no previous communication with any electric, we find that these two balls attract one another, and come into contact. The same actions are repeated between this second ball and a third, which may be presented to it; and so on in succession, but with a continued diminution of intensity. This diminution plainly indicates a diminished power, in consequence, as it would seem, of its being distributed among a number of bodies.

(17.) In the prosecution of these experiments, therefore, the effects will be more distinct, if, instead of small pith balls, we employ a globe of metal of larger size, which will allow of the reception of a considerable quantity of this electric influence by contact with the excited electric. A globe, suspended by silk threads, as the pith balls are, and which has extensively touched the electric, will act upon these balls precisely in the same way as the original electric would have acted upon them, and may accordingly be substituted for it in all these experiments. It is, indeed, exactly in the same condition as the globe rubbed by an electric, already mentioned. (§ 11.)

(18.) From the whole of these facts we necessarily infer that the electric has imparted to the ball or globe which came in contact with it, properties exactly similar to those which had been excited in itself by friction. By repeated contact with a number of bodies, an excited electric is found to lose its electrical powers in the same degree as these powers have been acquired by the bodies themselves; and fresh excitation alone can renew them. It is evident, then, that the unknown agent, which we have termed *Electricity*, is capable of transference, in the same sense in which we speak of heat being communicated or transferred from one body to another, and that, like heat, it is weakened by diffusion among a number of bodies.

(19.) If the electrified ball be touched with the finger, it will be deprived of the whole of its electricity, which will pass into the body of the person who touches it. It is now reduced to its original or natural state, and is again susceptible of being attracted, either by an excited electric, or by another body to which electricity has previously been communicated.

If the electrified body, instead of being touched with the finger, had been touched by a rod of metal held in the hand, the effect would have been the same in both cases: hence we may infer that the metallic rod is capable of conveying away from the body the whole of its electricity. But if a glass rod be substituted, the result is very different; the body touched is found to retain the whole of its electricity, notwithstanding the contact of the glass rod. We are thus led to the conclusion that some substances, such as glass, are incapable of conducting electricity; while others, such as the metals and the human body, readily convey that influence.

(20.) It is invariably found that all *electrics* are, at the same time, *non-con-*

ductors. Conductors, on the other hand, are *non-electrics.* The two qualities of a capability of excitation, and a power of conducting electricity, appear to be incompatible with each other—for the one is always found to diminish in proportion as the other increases. The permanence of electricity in metallic bodies, which are suspended in the air by silk threads, shows that the air as well as the silk is a non-conductor. Bodies which are in this way surrounded on all sides by non-conductors are said to be *insulated.* When this condition is not observed, that is, when the body is in contact with conducting bodies which communicate with the earth, its electricity will escape by the channel which is thus opened for it, and will be lost by diffusion in the mass of the earth, which is formed of conducting materials, and which may be regarded as the great reservoir both for the absorption and supply of electricity. Hence we see why it is not possible to accumulate electricity in a conducting body while it is held in the hand, and why electrics alone are capable of permanent excitation.

(21.) The insulating power of atmospheric air depends principally upon two circumstances, its density and its dryness. Air with the density which it has under the ordinary pressure of the atmosphere, if perfectly dry, is a remarkably good insulator, even although it be rapidly renewed on the surface of the electrified body. This is shown by an experiment of Franklin's, in which he whirled an electrified ball round his head, by means of a silk line, with great rapidity, so as to make it perform many hundred revolutions, without being able to perceive that it had thereby lost any sensible portion of its electricity. Neither an increase, nor a diminution of temperature, appears to lessen its insulating power. But in proportion as the air is rarefied by the removal of the superincumbent pressure, its power of confining electricity diminishes, till, at last, when the rarefaction is very great, it opposes scarcely any resistance to the passage even of very feeble electricity; and it may be then classed among conductors. This is the case with the imperfect vacuum produced by the air-pump, from which it is almost impossible to exclude minute quantities of air. Even in the space left in the upper part of the tube of a barometer by the descent of the mercury, or the Torricellian vacuum, as it is called, there is in general present a minute portion of air, as well as of mercurial vapour, which are sufficient to conduct electricity. Small globules of air usually adhere to the mercury, and to the sides of the tube; and these, upon the removal of pressure, expand into an atmosphere. It has been asserted by Mr. Morgan that if great care be taken to remove every source of error, by the employment of very pure mercury, and by boiling it for a long time in the tube, a perfect vacuum may be obtained, which does not conduct electricity. His experiment, however, was made long ago, and requires careful repetition, before the result can be confided in.

(22.) The circumstance which chiefly determines the conducting power of common air is that of its containing a greater or less quantity of moisture. Water is a very good conductor of electricity; and that portion which is suspended in the air tends powerfully to carry off electricity from the bodies which are charged with it, and which are surrounded by air. Moisture also easily attaches itself to glass and other electrics, and deprives them of the power of insulation. Hence, the same experiments which succeed in a clear dry day, will often fail when tried in damp weather: and hence we see the utility of previously drying every part of the apparatus, in order to exclude as much as possible the interference of moisture.

(23.) The conducting powers of most bodies are influenced by changes of temperature, and also of form. Thus, although water in its liquid state is a good conductor, yet, when congealed, in the form of ice, its conducting powers are much impaired; and at a very low temperature, namely, at —13° of Fahrenheit's scale, ceases altogether. Mr. Achard, who observed this fact, formed ice of this temperature into a spheroid, and mounting it upon an axis, was able to excite it by friction as any other electric. On the other hand, by raising the temperature of water, its conducting powers are increased. Charcoal is also found to transmit electricity with more facility when hot, than when cold. Glass, which is a non-conductor when cold, becomes a tolerably good conductor when heated to redness; and a similar change takes place in sulphur and in resinous bodies when melted; and also in baked wood when heated. Reducing substances to

powder has often an effect upon their powers of conducting electricity. Snow conducts less readily than ice of the same temperature. The same is the case with powdered charcoal, when compared with the same substance in its entire state. But glass, on the contrary, acquires some conducting power by being pulverized, as was ascertained by Van Swinden, who extended the same observation to sulphur.

Many bodies, which, in their usual state, are good conductors of electricity, lose this power when they are made very dry. This is the case with recent vegetable and animal substances, their conducting power appearing to be derived solely from the fluids they contain.

(24.) Strictly speaking, there is no substance hitherto known that is perfectly impervious to electricity; for the intensity of that agent may be so increased as to force it, for a certain small distance, through all bodies: neither is there any body in which the conducting power is infinitely great; that is, which opposes no resistance to the transmission of electricity. If the degree of conducting power which bodies possess could be ascertained with sufficient precision, they might be arranged in progressive order; but the present state of our knowledge affords only an approximation to such a series. As a table of this kind, however, with all its imperfections, may be of great use, we subjoin the following, in which the different bodies are arranged in one series, beginning with those which have the greatest conducting power, and terminating with those that have the least. The order in which they possess the power of insulating is, of course, the reverse of this.

Catalogue of Bodies in the Order of their conducting Power.

The perfect, or least oxidable metals.
The more oxidable metals.
Charcoal prepared from the harder woods, and well burned.
Plumbago.
The concentrated mineral acids.
Powdered charcoal.
Dilute acids.
Solutions of metallic and neutral salts.
Metallic ores.
Animal fluids.
Pure water.
Snow.
Living vegetables.
Living animals.
Flame.
Smoke
Steam.
Metallic salts
Salts with alkaline or earthy bases.
Rarefied air.
Vapour of alcohol.
Vapour of ether.
Earths and stones in their ordinary state.
Pulverized glass.
Flowers of sulphur.

Dry metallic oxides.
Oils.
Vegetable ashes.
Animal ashes.
Dry transparent crystals.
Ice below —13° Fahrenheit.
Phosphorus.
Lime.
Dry chalk.
Native carbonate of barytes.
Lycopodium.
Caoutchouc, or Indian rubber.
Camphor.
Siliceous and argillaceous stones in proportion to their hardness.
Dry marble.
Porcelain.
Baked wood.
Dry atmospheric air, and other gases.
White sugar, and sugar crystallized.
Leather.
Dry parchment.
Dry paper.
Cotton.
Feathers.
Hair, especially that of a living cat.
Wool.
Dyed silk.
Bleached silk.
Raw silk.
Transparent gems.
Diamond.
Talc.
Metallic vitrifications.
Glass, and other vitrifications.
Fat.
Wax.
Sulphur.
Resins, and bituminous substances.
Amber.
Gum-lac.

Although the precise point in the scale which forms the separation between conducting and insulating bodies must, of course, be somewhat indefinite, we have endeavoured to mark it by the division in the above table.

(25.) It appears, from the experiments

of Mr. Coulomb, that a thread of gum-lac is the most perfect of all insulators, and is ten times more effectual than a silk thread as dry as it can be made; for the former, when only one inch and a half in length, insulated as well as a fine silk thread of fifteen inches. When the thread of silk was dipped in fine sealing-wax, it was equal in power to a thread of pure lac of four times its length. Professor Robison found that the conducting power of silk thread depends greatly on its colour; or, in other words, on the nature of the drug with which it is dyed. When of a brilliant white, or a black, its conducting power is the greatest; and a high golden yellow, or a nut brown, renders it the best insulator. Glass, even in its dryest state, and in situations where it was impossible that moisture could have access to it, is stated by the same author to insulate considerably better than silk; and when drawn into a slender thread, and coated with gum-lac, it acted as well as a thread of lac of one-third of the length. It was found, however, at the same time, that extreme fineness was requisite; for it dissipated in proportion to the square of its diameter. The insulating power of glass is remarkably injured by having a bore, however fine, unless that bore admits of being also coated with lac. Human hair, when completely freed from every thing that water could wash out of it, and then dried by lime, and coated with lac, was equal to silk. Fir, cedar, larch, and the rose-tree, when split into filaments, and first dried by lime, and afterwards baked in an oven, which just made paper become faintly brown, seemed scarcely inferior to gum-lac. The white woods, as they are called, and mahogany, were much inferior. Fir, baked and coated with melted lac, seems, therefore, the best support when strength is required. The lac may be rendered less brittle by a minute portion of pure turpentine, which has been cleared of water by a little boiling, without sensibly increasing its conducting power. Lac, or sealing-wax, dissolved in spirits, is far inferior, for these purposes, to what it is when melted by heat.

(26.) The laws which regulate the gradual dissipation of electricity from bodies in a state of imperfect insulation have been investigated with great ability by Coulomb. Three causes chiefly operate in depriving a body under these circumstances of its electricity:—First, the imperfection of the insulating property in the solids by which it is supported. Secondly, the contact of successive portions of air, every particle of which carries off a certain quantity of electricity. Thirdly, the deposition of moisture upon the surface of the insulating body, which establishes communications with its remote ends, and may be considered as virtually increasing its conducting power.

(27.) With regard to the first cause, Mr. Coulomb has completely ascertained that for all fine cylindrical fibres, such as hair, silk, filaments of gum-lac, &c. if the nature of the substance, the diameter of the fibre, and the dispersive state of the air are supposed constant, the length of the fibre requisite for the complete insulation of a given intensity of electricity, varies as the square of that intensity. Theory, therefore, leads to the conclusion that, however great may be the intensity, there is always a certain length beyond which a filament of any of these bodies becomes a perfect insulator; and we find, in practice, that by diminishing the intensity of the electricity, or increasing the length of the substance it has to traverse, a sufficiently accurate degree of insulation may be obtained. With respect to the second source of dissipation, it was found that in a given state of the atmosphere, as far as it could be determined by the indications of the barometer, thermometer, and hygrometer, the dissipation at each instant of time, varied directly as the intensity of the electricity.

(28.) There is one very material circumstance relating to the dissipation of electricity that should here be mentioned, although its explanation must be deferred till the principles on which it depends have been developed; and it is, that the power of retaining electricity in any body is much influenced by its shape. The form most favourable to its retention is that of a sphere; next to which is a spheroid, and a cylinder terminated at both ends by a hemisphere. On the other hand, electricity escapes most readily from bodies of a pointed figure, especially if the point projects to a distance from the surface. In such bodies it is scarcely possible, indeed, to accumulate any sensible degree of electricity, on account of its rapid dissipation from the point. In like manner pointed bodies receive electricity more readily than those of any other form.

§ 3. *Of the two species of Electricity.*

(29.) We have hitherto viewed electrical phenomena as arising from the operation of a single agent, which could be called into action, and transferred from one body to another. We have seen that bodies, which have received their electricity from excited glass, repel one another, and are likewise repelled by the excited glass. The same thing happens with respect to those bodies which have received their electricity from excited sealing-wax. But upon examining the action of any of the bodies belonging to the one set, upon any of those belonging to the other, we find, that instead of repelling, they attract each other. Thus, the ball which has received its electricity from the glass, attracts that which has been electrified by the sealing-wax, and is attracted by it; but, what is still more remarkable, the moment these balls have come into contact, provided they have both been electrified in the same degree, they cease at once to exhibit any signs of electricity, as if the electricities of both were suddenly annihilated by their mutual communication. Thus there appears to be two different, and, in some respects, opposite kinds of electricities; the one obtained from glass, the other from sealing-wax. Du Fay, by whom this distinction was first noticed, denominated the former the *vitreous*, and the latter the *resinous* electricity.

(30.) The mode of action which these two electricities exert on matter, may be expressed by the following law: namely, that *bodies charged with either species of electricity, repel bodies charged with the same species, but attract bodies charged with the other species; and that, at equal distances, the attractive power in the one case is exactly equal to the repulsive power in the other.*

Accordingly, if we wish to ascertain what is the species of electricity with which a given body is charged, we have only to approach it to a small insulated pith ball, which has previously been touched either with excited glass or with excited sealing-wax. If the body in question repel it in the former case, or attract it in the latter, its electricity is vitreous; if the contrary happens, it is resinous.

(31.) Although each of these two electricities, when taken separately, acts in a manner precisely similar to the other, they nevertheless exhibit in all their relations to each other a marked contrariety of nature. Hence they are naturally viewed as agents having opposite qualities, which completely neutralize one another by combination.

(32.) Another remarkable circumstance which characterizes these agents, is, that the excitation of one species of electricity is always accompanied by the excitation of the other; and both are produced in equal degrees. Thus, when glass is rubbed by silk, or flannel, just as much resinous electricity is produced in the silk, or flannel, as there is vitreous electricity produced in the glass; and whatever electrified bodies are repelled by the one are attracted in the same degree by the other. If one of the substances happen to be a conductor, and be held in the hand, the whole of the electricity which the friction excites in it will disappear as soon as it is produced, from its escaping through the body of the person holding it, and being lost in the earth. But if the precaution be taken of insulating the rubber, its electricity will become manifest, and is always found to be of the opposite species to that which is excited in the body which is rubbed.

(33.) Since the two surfaces rubbed acquire opposite electricities, it follows as a consequence of the law above stated, that they must attract one another; and this is found invariably to be the case. If a white and a black ribbon of two or three feet long, and perfectly dry, be applied to each other by their flat surfaces, and are then drawn repeatedly between the finger and thumb, so as to rub against each other, they will be found to adhere together, and if pulled asunder at one end, will rush together with great quickness. While united they exhibit no sign of electricity, because the operation of the one is just the reverse of that of the other, and their power is neutralized and inoperative. If completely separated, however, each will manifest a strong electrical power, the one attracting those bodies which the other repels.

(34.) The very act of separation is accompanied by appearances which indicate that considerable portions of the electricities excited on each of the surfaces fly back to the opposite surface, and by their union become as it were extinguished or inoperative; and it is only the remaining quantities which have adhered more tenaciously to the

surfaces, that retain their activity. When the experiment is made in the dark, flashes of light attend these sudden exchanges of electricity, passing between the two surfaces, and accompanied with a rustling noise.

(35.) Numberless experiments have been made with a view of ascertaining the conditions that determine the species of electricity excited in the respective bodies of which the surfaces are made to rub against each other, but they have led to no satisfactory conclusion. The mechanical configuration of the surface appears to have a greater influence in the result than the peculiar nature of the substance itself. If a plate of glass with a polished surface be rubbed against one which is roughened, the former always acquires the vitreous, and the latter the resinous electricity. No approach to an explanation of this peculiarity has ever been made. Smooth glass acquires vitreous electricity by friction with almost every substance, except the back of a cat, which gives it the resinous electricity; but roughened glass, if rubbed with the same substances, becomes charged with resinous electricity, while the rubbing bodies acquire the vitreous. Sealing-wax, rubbed with an iron chain, acquires, if polished, the resinous electricity; but if its surface is previously rough with scratches, the vitreous. Silk, rubbed by resin, takes the vitreous, but with polished glass, the resinous electricity. The following is a list of several substances which acquire vitreous electricity when rubbed with any of those which follow it in the order in which they are set down; and resinous electricity if rubbed with any of those which precede:—

The back of a cat.
Polished glass.
Woollen cloth.
Feathers.
Wood.
Paper.
Silk.
Gum-lac.
Roughened glass.

In the experiment just mentioned, in which a black and a white ribbon are rubbed together, the former is found to be resinously and the latter vitreously electrified. But if two pieces of the same ribbon of the same length be rubbed, the one being drawn lengthwise and at right angles over a part of the other, the one which has suffered friction in its whole length acquires vitreous, and the other resinous electricity. In like manner, when the whole length of the bow of a violin is drawn over a limited part of the string, the hairs of the bow exhibit a vitreous, and the string a resinous electricity, the body whose excited portion is of the least extent being generally found to be resinously electrified. But in truth, the slightest difference in the conditions of these and similar experiments on the species of electricity arising from friction, will be often sufficient to produce opposite results.

(36.) Electrical excitation may also be produced by the friction of liquids or of gases against solid bodies. This is the case when mercury is made to fall, in a fine shower, under the exhausted receiver of an air-pump, against the glass. If a current of atmospheric air be directed against a pane of glass, by means of a pair of bellows, the glass becomes vitreously electrified.

§ 4. *Induction.*

(37.) Another class of electrical phenomena must here be noticed. Whenever a body is charged with electricity, although it be perfectly insulated, and of course all escape of that electricity prevented, it tends to produce an electrical state of the opposite kind in all the bodies in its vicinity. Thus the vitreous electricity tends to induce the resinous electricity in a body that is situated near it; and this with greater energy, as the distance is smaller. This effect is termed the *induction* of electricity, and may be ranked among the general facts, or laws of the science. The further development of the consequences it leads to, must, for the present, be postponed, as we shall hereafter be better prepared to understand them. But there is one of its results which we shall now point out, as it refers immediately to the phenomena that have already occupied our attention.

(38.) If an electrified body, charged with either species of electricity, be presented to an unelectrified or neutral body, its tendency, in consequence of the law of induction, is to disturb the electrical condition of the different parts of the neutral body. The electrified body induces a state of electricity contrary to its own in that part of the neutral body which is nearest to it; and consequently a state of electricity similar to its

own in the remote part. Hence the neutrality of the second body is destroyed by the action of the first; and the adjacent parts of the two bodies, having now opposite electricities, will attract each other. It thus appears, that the attraction which is observed to take place between electrified bodies and those that are unelectrified, is merely a consequence of the altered state of those bodies, resulting directly from the law of induction; and that it is by no means itself an original law, or primary fact in the science.

(39.) The effects of induction will be in proportion to the facility with which changes in the distribution of electricity among the different parts of a body can be effected, a facility which corresponds with the conducting power of the body. Hence the attraction exerted by an electrified body upon another body previously neutral, will be much more energetic if the latter be a conductor, than if it be an electric, in which these changes can take place only to a very small extent. This is confirmed by the following experiment: suspend by fine silk threads of equal length, two small balls of equal dimensions, both made of gum-lac, but one having its surface covered with gold leaf. Place these two pendulums, as they may be called, at a little distance from one another, so as to admit of a comparison of their motions; and then present to them an excited electric, which may be either a tube of glass, or a cylinder of sealing-wax. It will at once be seen that the ball, with a metallic covering, which readily admits of the transfer of electricity from one side to the other, will be much more readily and powerfully attracted, than the other ball which allows of no motion in its electricity. The latter ball will, by slow degrees, however, assume electrical states of the same kind as the gilt ball, and will be feebly attracted. As this change is very slowly effected, so it is more permanent when once produced; and the plain ball adheres for a considerable time to the electric which has attracted it. The gilt ball, on the contrary, is sooner repelled, by its readily receiving the charge of electricity imparted to it by the electric. A degree of permanent electricity, however, is also induced on this ball, in consequence of its gradual penetration into the substance of the gum-lac.

Chapter II.

Theories of Electricity.

(40.) It is impossible to arrive at the full comprehension of the multifarious facts relating to any of the physical sciences without the aid of some leading principles, or modes of viewing them, by which their connexions can be represented to the mind, so as to combine them into an intelligible system. We begin by classing the different agents in nature, designating them by specific names; we next endeavour to conceive these agents as possessed of certain powers or qualities adapted to the production of the observed effects. In the case of light, for example, we may conceive the phenomena to result from the action of material particles, emanating in all directions from the luminous body, and obeying certain laws in their course; or we may adopt another hypothesis, namely, that they proceed from the undulations of an elastic medium pervading space. By employing either the one or the other of these hypotheses, we acquire great facility in tracing the connexions of the phenomena of optics, and retaining them in our minds. This advantage is not immediately dependent on the truth of the particular hypothesis we employ for that purpose: for, in the example before us, it is evident they cannot both be true, and yet they both answer this end. But, of course, the utility of an hypothesis will be proportionate to the degree of exactness with which it accords with the phenomena. No inconvenience can arise from its adoption, as long as we bear in mind that our reasonings are founded on a mere hypothesis, and as long as we hold ourselves in readiness to abandon it, the moment we meet with facts with which it is decidedly inconsistent.

(41.) The hypothesis which naturally suggests itself for the explanation of electrical phenomena is that of a very subtile and highly elastic fluid, pervading the earth and all other material bodies, but itself devoid of any sensible gravity. We must suppose this fluid to be capable of moving, with various degrees of facility, through the pores or actual substance of different kinds of matter. In some, as in those we call *conductors*, or *non-electrics*, such as the metals, it moves without any perceivable obstruction: but, in glass, resin, and, in general, in all bodies

called *electrics*, or *non-conductors*, it moves with great difficulty. Moreover, as the phenomena appear to point out the existence of two distinct kinds of agencies, we may further assume that there are two distinct species of electric fluid, which we shall, for the present, name the *vitreous* and the *resinous electricities*. They must each have, when separate, the same general properties as have already been enumerated; but, in relation to each other, there must be a complete contrariety in their natures, so that when combined together, their actions on the bodies in their vicinity, or on the particles of electric fluid contained in those bodies, are exactly balanced; and all visible action ceases. It is in this state of union, in which they perfectly neutralize one another, that they exist in bodies which may be said to be in their *natural state* with regard to electricity.

(42). Thus, then, may the problem be solved, in which it is required to conceive an agent, analogous, in many respects, to other known agents, and to assign to it such properties as will, in their results, correspond to all the observed phenomena. In order to apply to it this latter test, we must trace all the consequences which flow from the suppositions we have made, and strictly compare them with the facts both as presented to us by nature, and as resulting from experiment. These facts, it will be recollected, are reducible to those of excitation, attraction, and repulsion, distribution, induction, and transference.

(43.) *Excitation.* From various causes, of which the friction of surfaces is one, the state of union in which the two electricities naturally exist in bodies, is disturbed; their latent powers are called forth by their separation; the vitreous electricity is impelled in one direction, while the resinous is transferred to the opposite side; and each can now manifest its peculiar energies. When accumulated in any body, or part of a body, each fluid acts in proportion to its relative quantity, that is, to the quantity which is in excess above that which is still retained in a state of inactivity by its union with electricity of the opposite kind. Thus when glass is rubbed with a metallic amalgam, a portion only of the electricities at the two surfaces is decomposed; the vitreous electricity resulting from this decomposition attaches itself to the glass; the resinous, to the amalgam. What remains in each surface undecomposed continues to be quite inert, and has no other influence on the phenomena, than being ready, on the continuance of the decomposing action, to furnish a fresh supply of both fluids to the bodies in the vicinity.

(44.) *Distribution.* Each of these fluids, being highly elastic, their particles repel one another with a force which increases in proportion as their distance is less: and this force acts at all distances, and is not impeded by the interposition of bodies of any kind, provided they are not themselves in an active electrical state. From the most careful analysis of the phenomena, it has been deduced that the exact law of this force is the same as that of gravitation, namely, that its intensity is inversely as the square of the distance.

The mode in which the electricity imparted to a conducting body, or to a system of conductors, is distributed among its different parts, is in exact conformity to the results of this law, as deduced by mathematical investigation. But we reserve the examination of this subject for a future chapter.

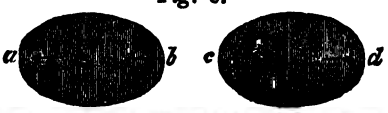
While the particles of each fluid repel those of the same kind, they exert an equally strong attraction for the particles of the other species of electric fluid. This attraction, in like manner, increases with a diminution of distance, and follows the same law as to its intensity, namely, that of the inverse ratio of the square of the distance. This force, also, is not affected by the presence of any intervening body.

(45.) *Transference.* Since the two electricities have this powerful attraction for each other, they would always flow towards each other and coalesce, were it not for the obstacles that are opposed to their motion by the non-conducting properties of electrics. When these obstacles are overcome, and a free channel is open for the passage of the electricities, they rush into union with great force and velocity, producing, in their transit and confluence, several remarkable effects. After their coalescence, their power seems to be at once annihilated, or, more properly speaking, it remains dormant, until called into play by the renewed separation of the fluids.

(46.) *Attraction and Repulsion.* The repulsion which is observed to take place between bodies that are insulated

and charged with any one species of electricity, for other bodies similarly charged, is derived from the repulsive power which the particles of this fluid exert towards those of their own species. Let us suppose a body charged with electricity to be suspended in the air, or otherwise surrounded by a non-conducting medium, which allows it to move freely. As long as this body remains alone, the outward pressure which the electric fluid exerts against the insulating medium that confines it, will, by the laws of hydrostatics, be equal on all sides; and the body, thus balanced by equal and opposite pressures, will have no tendency to move. But if another body, similarly circumstanced, be brought near it, the repulsive action between the similar electricities contained in these bodies, will diminish the outward pressures of each fluid against the sides of the bodies, (*b, c, fig.* 8.) which are adjacent to each

Fig. 8.



other; and it will, at the same time, increase the outward pressure on the opposite or remoter sides (*a, d.*) Both these causes conspire to destroy the equilibrium; each body is impelled in the direction of the preponderating force, that is, in a direction from the other body; and an effect, which may be called repulsion, takes place. The very same explanation, it is evident, applies to both kinds of electricity, their properties being in this respect exactly alike.

If, on the other hand, a body charged with vitreous electricity be presented to one that is charged with resinous electricity, the attraction of these two fluids will diminish the outward pressure on the remote sides of the bodies, and increase it on the adjacent sides; hence, the bodies will be urged towards each other, and motions indicative of attraction will result. Thus, in all cases, do the movements of the bodies represent the forces themselves which actuate the particles of the developed electricities they contain.

(47.) *Induction.* The law of induction is a direct consequence of the hypothesis we are considering. Wherever one of the electricities exists in an active state, it must repel the particles of the same electricity in all surrounding bodies, and attract those of the opposite species: or, in other words, it tends to decompose their united electricities, accumulating the electricity of the opposite species towards the nearest side, and impelling that of the same species towards the remote side. The body thus acted upon is no longer neutral, although it contains, on the whole, its natural quantities of both electricities; but, in consequence of their partial distribution, electrical appearances will be exhibited in its different parts. The further prosecution of this branch of the subject must also be postponed to a subsequent chapter, our present object being merely to point out, in a general way, the coincidence of the fundamental facts with the proposed theory.

(48.) Thus far we have proceeded upon the hypothesis of there being two distinct electric fluids, having certain properties in common, but each being characterized by a certain modification of these properties. It is, however, equally possible to account for all the phenomena with the same exactness, on the supposition of their resulting from the agency of a single electric fluid. This simplification of the theory may be considered as the discovery of the immortal Franklin, although it had occurred at the same period to Dr. Watson; for it was Franklin who first pointed out the mode in which it might be successfully applied to explain some of the most remarkable phenomena of the science. Several particular points in his theory, as he originally proposed it, were defective, and were found on strict examination to be at variance with ascertained facts. It is to Æpinus and to Cavendish that we owe the rectification of these errors: and the theory of Franklin, as thus amended, whatever alterations the future progress of discovery may oblige us to make in it, will ever remain one of the most beautiful specimens of this kind of reasoning which philosophy has produced. Of this hypothesis we shall now present a brief outline; and point out the mode in which it explains the phenomena.

(49.) We set out, then, with supposing that there exists in all bodies a subtile fluid, which we shall call the *electric fluid;*—that its particles repel one another with a force varying inversely as the square of the distance;—that they attract the particles of all

other matter, or some specific ingredient in that matter, with a force following the same law of the inverse square of the distance;—that this fluid is dispersed through the pores of bodies, and from some unknown peculiarity, can move through them with various degrees of facility, according as they are conductors or non-conductors. Bodies are said to be in their natural state with regard to electricity, when the repulsion of the fluid they contain for a particle of fluid at a distance is exactly balanced by the attraction of the matter in the body for the same particle. In this state they may be considered as *saturated* with the electric fluid. Whenever they contain a quantity of fluid greater than this, they are said to be *positively electrified*, or to have *positive electricity*. When, on the other hand, there is a quantity less than that required for saturation, the body is said to be *negatively electrified*, or to have *negative electricity*. In the former case, it is the fluid that is redundant, or in excess; in the latter, it is the matter which is left unsaturated that should be considered as the redundant principle. The state of positive electricity, then, consists in a redundance of fluid, or in matter that is *over-saturated*, as it has been termed; that of negative electricity, in a deficiency of fluid, or in matter *under-saturated*, or, what is an equivalent expression, in *redundant matter*. In mathematical language, the former condition may be expressed by the sign *plus;* the latter by that of *minus*. In considering the mutual electrical actions of bodies, the portions in which the matter and the fluid mutually saturate each other, need not be taken into account, since their actions, as we have seen, are perfectly neutralized: and we need only attend to those of the redundant fluid and the redundant matter.

(50.) When a body contains more than its natural proportion of electric fluid, the surplus will, by the repulsive tendency of its particles, overflow and escape, if such escape be allowed, until the body is reduced to its neutral state. When under-saturated, the redundant matter will attract fluid from all quarters from which it can receive it, until it is again brought to its neutral state. This efflux, or influx, is prevented either when the body is surrounded on all sides by substances, through the pores of which the fluid cannot pass, or when the body itself is of that nature.

(51.) The mutual recession of two positively electrified bodies is a direct consequence of the repulsion of the redundant fluids contained in each, which, being attached to the matter by their attraction for it, impel it in the direction of their own repulsion. In the same way the mutual approximation of two bodies in opposite electrical states is the immediate effect of the attraction of the redundant fluid in the one, for the redundant matter in the other; and *vice versâ*, for this attraction is mutual.

(52.) A difficulty does, indeed, occur when we attempt to apply the theory to the case of two bodies which are both in a state of negative electricity, that is, in which there exists in both certain quantities of matter unsaturated with electric fluid. What action does the theory, as hitherto stated, point out as the result in this particular case? Plainly none. All those portions of the matter of each body which are still saturated, together with the fluid which saturates them, can have, as we have already seen, no effect either of attraction or repulsion. The only active element is the unsaturated matter; but the hypothesis does not assign any action of this matter upon other matter at a distance. Yet we learn from experience that the bodies, under these circumstances, actually repel one another. In order, therefore, to render the hypothesis conformable to fact, we are obliged to annex to it another condition; namely, that the particles of simple matter, that is, of matter uncombined with the electric fluid, exert a repulsive action on one another. It is singular that so acute a mind as that of Franklin should not have discerned this defect in his own theory, or perceived that this further condition was absolutely requisite for the explanation of the phenomena. Without it, indeed, we should be unable to explain the want of action between two neutral bodies; for the repulsion of the fluids in both bodies being balanced by the attraction of the fluid in the one for the matter in the other, the remaining attraction of the fluid in the second body for the matter in the first would be uncompensated by any repulsion, and the forces would not be held in equilibrium, as we find they really are.

(53.) The law of electrical induction is an immediate consequence of the Franklinian theory. When a body charged with electricity is presented to a neutral body, the redundant fluid of

the former exerts a repulsive action on the fluid in the latter body; and if this happens to be a conductor, it impels a certain portion of that fluid to the remote end of this body, which becomes at that part positively electrified; while its nearer end, which the same fluid has quitted, is consequently in the state of negative electricity. If the first body had been negatively electrified, its unsaturated matter would have exerted an attractive force on the fluid in the second body, and would have drawn it nearer to itself, producing an accumulation or redundance of fluid at the adjacent end, and a corresponding deficiency at the remote end: that is, the former would have been rendered positive, and the latter negative. All this is exactly conformable to observation.

(54.) The phenomena of transference are easily explicable on this hypothesis; and they arise from the destruction of the equilibrium of forces, which confined the fluid to a particular situation or mode of distribution.

(55.) There is, indeed, no fact explicable by the hypothesis of a double fluid, which is not explained with equal facility by that of a single fluid, with the condition already stated. The explanation by the first is easily converted into an explanation by the second, by substituting the expressions of *positive* and *negative* for those of *vitreous* and *resinous electricities*; and considering the action of the latter as arising from the influence of redundant or unsaturated matter, to which is ascribed in the Franklinian hypothesis a similar operation to that of the resinous electricity in the hypothesis of Du Fay. The hypothesis of a single fluid has, it must be allowed, the advantage of greater simplicity: but, on the other hand, it lies open to the objection of its involving a condition which appears, at first view, to be at variance with our preconceived notions of the primary laws of matter, and more especially with that of gravitation; namely, that which implies the mutual repulsion of its particles when void of electricity.

When viewed as a mere hypothesis calculated to facilitate our comprehension of the phenomena and of their connexions, it is a matter of indifference which we employ, for they will either of them answer the purpose. In our future explanations we shall, in general, adhere to the language of the Franklinian theory, as being the simplest, and generally the most convenient; and because a conversion of terms the reverse of that just now pointed out will in all cases enable us to supply the explanation of the same phenomenon according to the theory of Du Fay. As to the question which of these two hypotheses approaches the nearest to the real state of things, we are not yet prepared to discuss the arguments that could enable us to decide it; and we must, therefore, wait till we can resume the subject in the sequel.

The further development of these theories, and of the law of induction, in particular, must, for the present, be postponed, since they require us to be acquainted with many practical details relating to the accumulation of electricity, and its management when applied to various objects of experimental research.

Chapter III.

Electrical Machines.

(56.) The essential parts of an instrument for procuring large supplies of electricity for the purposes of experiment, or an *electrical machine*, as it is called, are the electric, the rubber, the prime conductor, the insulator, and the machinery for setting the electric in motion.

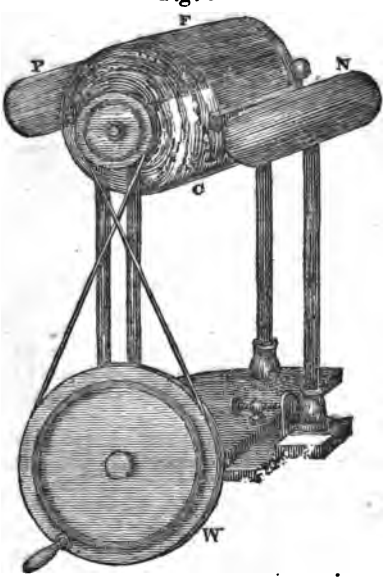
(57.) The electric, by the excitation of which the electricity is to be developed, may be made of various materials. Globes of sulphur were employed by the earlier electricians for that purpose; but polished glass is found, on the whole, to be the most convenient substance. The original form given to it by Hauksbee, who was the inventor of the electrical machine, was that of a globe, which he caused to revolve upon a vertical axis. The most convenient forms, however, are those of a hollow cylinder, or of a flat circular plate, revolving upon a horizontal axis. When used in the form of a globe or cylinder, it has sometimes been found advantageous to line the inside of it with a thin layer of a resinous composition, consisting of four parts of Venice turpentine, one of resin, and one of bees' wax. This must be introduced in sufficient quantity into the inside of the globe or cylinder, and, when the glass is brought gradually to an equal degree of heat throughout the melted substances, is allowed to spread itself over the interior surface, by turn-

ing the globe or cylinder about its axis. The principal use of such a coating is to improve bad machines, for it is not required in good ones.

The earlier electricians contented themselves with using the hand as a rubber, till a cushion was introduced for that purpose by Professor Winkler, of Leipsic. The cushion is usually made of soft leather, generally basil skin, stuffed with hair or wool, so as to be as hard as the bottom of a chair, but yet sufficiently yielding to accommodate itself, without much pressure, to the surface of the glass to which it is applied.

(58.) Of cylindric machines, the simplest and most perfect construction is that invented by Nairne, and which is represented in *fig.* 9. The glass cylinder C is from 8 to 16 inches in diameter, and

Fig. 9



from one to two feet long, supported, for the purpose of insulation, on two upright pillars of glass, which are fixed to a firm wooden stand. Two hollow metallic conductors P, N, equal in length to the cylinders, are placed parallel to it, one on each side, upon two insulating pillars of glass, which are cemented into two separate pieces of wood that slide across the base so as to allow of their being brought within different distances from the cylinder. To one of these conductors N, the cushion is attached, being fastened to it by the intervention of a bent spring, the purpose of which is to keep it equally pressed against the cylinder in every part of its revolution. The pressure of the cushion is also further regulated by an adjusting screw adapted to the wooden base, on which the glass pillar that supports the conductor is fixed. From the upper edge of the cushion there proceeds a flap F of thin oiled silk, which is sewed on the face of the cushion about a quarter of an inch from its upper edge. It extends over the upper surface of the glass cylinder to within an inch of a row of metallic points, proceeding like the teeth of a rake from a horizontal rod, which is fixed to the adjacent side of the opposite conductor P. The motion of the cylinder must always be given in the direction of the silk flap; and it may be communicated either by a single handle, or by a multiplying wheel W, as in the figure: the latter produces more electricity in the same time, but the labour of turning is increased nearly in the same proportion. On some accounts it is more convenient to place the conductor to which the rubber is not attached, at right angles to the cylinder; and this is the plan adopted in the common electrical machines.

(59.) The conductor P, to which the rubber is not attached, is generally called the *prime conductor*, or the *positive conductor*, as the electricity with which it becomes charged is positive. It is a cylindrical tube, each end terminating in a hemisphere. There is no advantage in its being made of solid materials, for the electricity is contained only at the surfaces. It may be made of thin sheet brass, or copper, or tin, or of pasteboard, covered with gold leaf or tin foil. Care must be taken that its surface be free from all points and asperities; and the perforations which are made in it, and which should be about the size of a quill, for the purpose of attaching wires, and other kinds of apparatus, should have their edges well rounded and smoothed off. For the more perfect insulation of the conductor, it is advisable to apply upon the glass pillar which supports it, a varnish of gum-lac, or of sealing wax.

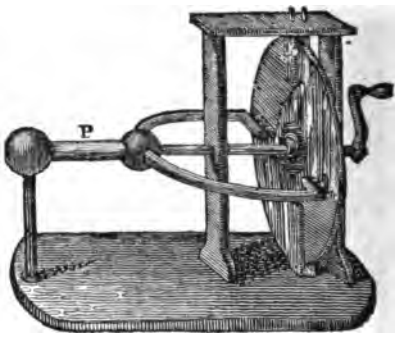
(60.) The degree of excitation produced in the glass depends much upon the substance employed as a rubber. Mr. Singer observes that dry silk is very efficacious, but that the most powerful effects are obtained by the use

of an amalgam of tin, zinc, and mercury, applied by means of hog's lard, to the surface of leather or oiled silk. That part of the cushion which comes in contact with the glass cylinder, should be coated with an amalgam of this kind, spread evenly over its surface, until level with the line formed by the seam which joins the silk flap to the face of the cushion. No amalgam should be placed over this seam, nor on the silk flap; which last should be wiped clean whenever the continued motion of the machine shall have soiled it, by depositing dust or amalgam on its surface. The same attention is requisite to the surface of the glass, which often becomes covered with black spots and lines, more particularly when the amalgam has been recently applied. It is essential to remove these as often as they are formed in any quantity, since they tend to lessen the power of the machine. The surface of the amalgamated cushion is also soon soiled; for the excited glass constantly attracts dust from surrounding bodies, and this dust is collected by the rubber as the glass passes it. If the dust is removed after every course of experiments, by separating the cushion from the negative conductor, and gently rubbing its surface, and the surface of the silk flap, with a dry linen cloth, the machine may be kept in good order without a frequent renewal of the amalgam; such renewal being only necessary when that which has been applied becomes irregularly distributed over the cushion, or impregnated with dust.

(61.) The amalgam recommended by Mr. Singer, is made by melting together one ounce of tin and two ounces of zinc, which are to be mixed, while fluid, with six ounces of mercury, and agitated in an iron, or thick wooden box, till cold. It is then to be reduced to very fine powder in a mortar, and mixed with a sufficient quantity of hog's lard to form it into a paste. When amalgams have a large proportion of mercury, their action is variable and transient. The best cement for attaching the cylinder to its pivots, is made by mixing five pounds of resin, one pound of bees' wax, one pound of red ochre, and two table-spoonfuls of plaster of Paris. The ochre and plaster of Paris should be well dried, and then added to, and alternately mixed with the other ingredients, when they are in a state of fusion.

The plate machine, *fig.* 10, was originally proposed by Dr. Ingenhouz, and has been since much improved by Cuthbertson. This machine, in its most per-

Fig. 10.



fect form, consists of a circular plate of glass, turning on an axis that passes at right angles through its centre: it is rubbed by two pair of cushions, fixed at opposite parts of the circumference by elastic frames of thin mahogany, which are constructed so as to press the glass plate between them with the requisite force, by means of regulating screws. A brass conductor P, supported by glass, is fixed to the frame of the machine, with its branched extremities opposite to each other, and near the extreme diameter of the plate, in a direction at right angles to the vertical line of the opposite cushions. The branched extremities of the conductor are furnished with pointed wires, that serve to collect the electricity from the surface of the excited plate.

(62.) It is not quite determined which of these two arrangements affords the greatest quantity of electricity from the same surface; but the cylinder is less expensive, and less liable to accidents than the plate, and it appears to possess nearly equal power.

(63.) From what has already been explained of the general laws of electricity, the mode in which these machines act will readily be understood. The friction of the cushion against the glass cylinder produces a transfer of electric fluid from the former to the latter; that is, the cushion becomes negatively, and the glass positively, electrified. The fluid which thus adheres to the glass, is carried round by the revolution of the cylinder; and its escape is at first prevented by the silk flap

which covers the cylinder, until it comes to the immediate vicinity of the metallic points, which being placed at a small distance from the cylinder, absorb nearly the whole of the electricity as it passes near them, and transfer it to the prime conductor. Positive electricity is thus accumulated in the prime conductor, while the conductor connected with the cushion, being deprived of this electricity, is negatively electrified.

But if both these conductors are insulated, this action will soon have reached its limit: for when the cushion and its conductor have been exhausted of their fluid to a certain degree, they cannot by the same force of excitation supply any further quantity to the glass. In order to enable it to do so, we must replenish it, as it were, that is, restore to it a quantity equal to what it has lost. This purpose will be answered by placing it in communication with a conducting body of large dimensions; or, what is still more effectual, by making it communicate with the earth, which is an inexhaustible source of electric fluid. In order, therefore, to supply the prime conductor with a constant stream of electricity, we must destroy the insulation of the cushion, by placing on the conductor to which it is fixed, a metallic chain, or wire, extending to the ground. If, on the other hand, we wish to obtain negative electricity, by means of the same machine, we must keep the negative conductor insulated, and connect the prime conductor with the ground, in order to allow the fluid to escape from it as soon as it is collected from the cylinder. The fluid will thus continue to be drawn without interruption from the negative conductor, as it now meets with no impediment to its discharge on the opposite side of the machine.

That the quantity of positive electricity produced in one conductor is exactly equal to that of the negative electricity in the other, is proved by the fact that, if the two conductors are connected by a wire, no signs of electricity are obtained in any of the conductors on turning the machine: but if the wire be not continuous, but interrupted by short intervals, a succession of sparks appear at each interval, indicating the passage of a stream of fluid from the one side to the other of the apparatus.

(64.) A person standing on a stool with glass legs is thereby insulated; and if, in this situation, he touch the prime conductor, either with his hand, or through the intermedium of a metallic rod, or chain, he may be considered as forming part of the same system of conductors. When the machine is worked, therefore, he will partake with the conductor of its charge of electricity, and sparks may be drawn from any part of his body by the knuckle of any other person who is in communication with the ground.

Chapter IV.

Effects of Electrical Attraction and Repulsion.

(65.) Having obtained, by the electrical machine, the means of accumulating considerable quantities of electricity, we are enabled to multiply and extend our observations of the phenomena, and to examine with more precision their correspondence with the results of theory. The effects of electrical attractions and repulsions may be exhibited much more distinctly, and on a larger scale than with the simpler instruments we had previously employed. The experiments formerly mentioned on the alternate approach and recession of light bodies, may be repeated with either conductor of the machine, when charged with electricity, and we may note with more accuracy the differences which occur in the rapidity with which the changes from one electrical state to another take place according as the bodies are more or less good conductors of electricity. A pith ball, or a fragment of gold leaf, is very strongly and immediately attracted by the electrified conductor, and the instant after it has come into contact with it, is repelled; but it is now attracted by the other bodies in its neighbourhood, to which it communicates its own electricity, and then is again in a state to be influenced by the conductor, and to be again attracted: and this alternation of effects will continue as long as the conductor remains charged.

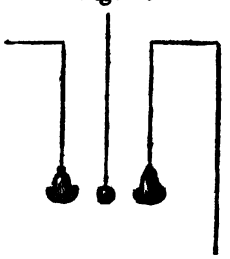
(66.) These alternate and rapid movements are best seen by placing these small bodies between two metallic plates, placed as in fig. 11, the one over the other, at a certain distance; the upper one communicating with the prime conductor, the lower one with the ground. If figures of men and women are cut out of paper and placed between

the two plates, they will exhibit a rapid dance, while they fetch and carry the electricity from the upper to the lower plate; or contrariwise, if the conductor be in the negative state.

Fig. 11.

(67.) This alternation of attractions and repulsions accompanying the transferring electricity by moveable conductors, is also illustrated by the motions of a ball (*fig.* 12.), suspended by a silk

Fig. 12.



thread, and placed between two bells, of which the one is electrified, and the other communicates with the ground. The alternate motion of the ball between the two bells will produce a continued ringing. As thus described, it is a mere toy, but the same arrangement has been applied to the philosophical purpose of giving notice of changes taking place in the electrical state of the atmosphere.

(68.) The mutual repulsion of bodies that are similarly electrified gives rise to many amusing appearances. The filaments of a feather will separate from each other and diverge, when electrified, presenting a singular and unnatural appearance. A small figure in the shape of a human head, covered with hair, when placed upon the conductor and electrified, will exhibit the appearance of terror from the general bristling up and divergence of the hair. A lock of wool highly charged with electricity will, in like manner, swell out to a large size, in consequence of the mutual repulsion of the filaments which compose it. On approaching a needle to it, held in the hand, whereby its electricity is quickly drawn off, the cotton will suddenly shrink into its original dimensions.

(69.) We have already adverted to the effects of fusion in rendering some bodies conductors, which in their solid state had the contrary property. This is the case with sealing-wax; and accordingly, if melted sealing-wax be electrified, its particles will tend to separate by their mutual repulsion, and to draw out into filaments. Let a piece of sealing-wax be fixed on the end of a wire, and be set fire to, but the flame immediately afterwards blown out. While the surface of the wax is still melted, present it, at the distance of some inches, to the electrified conductor, a number of extremely fine filaments will immediately dart out from the sealing-wax to the conductor, on which they will be condensed into a kind of net-work resembling wool. If the wire with the sealing-wax be stuck into one of the holes of the conductor, and a piece of paper be presented at a moderate distance to the wax, just after it has been ignited, on setting the machine in motion, a net-work of wax will be formed on the paper. The same effect, but in a slighter degree, will be produced, if the paper be briskly rubbed with a piece of Indian rubber, and the melting sealing-wax be held pretty near the paper immediately after it has been rubbed. If the paper, thus covered with filaments of sealing-wax, be gently warmed before the fire, the wax will adhere to it, and exhibit permanently the result of the experiment. Still more beautiful are the appearances produced by camphor subjected to a similar process. For the purpose of obtaining them, a spoon, holding a piece of lighted camphor, must be kept electrified by working the machine, while it communicates with the conductor; the camphor will then throw out curious ramifications, which appear to shoot like those of a vegetable.

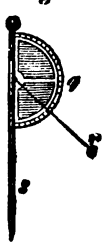
(70.) It is on the same principle that

the escape of a conducting fluid, such as water, through a narrow aperture, is promoted by electrifying it. If a small metallic vessel filled with water be suspended from the prime conductor, and there be placed in the water one end of a glass syphon, with a capillary bore of such a diameter as that the water will scarcely drop from it; upon turning the cylinder of the machine so as to convey electricity to the vessel and its contents, the water immediately flows in a stream, and, if the electrical charge be very powerful, the descending current will be seen to separate into several branches.

(71.) If a sponge, saturated with water, be suspended from the prime conductor, the water will at first only drop gradually from the sponge; but when the conductor has become strongly electrified, the drops will fall plentifully, and, in the dark, will produce the appearance of a luminous shower of rain.

(72.) Advantage is taken of the repulsive property of electrified bodies for the construction of an *Electrometer*, or instrument adapted to measure the intensity of the electricity they may contain. Henley's electrometer (*fig.* 13.)

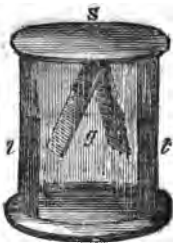
Fig. 13.



consists of a slender rod of very light wood, *r*, serving as an index, terminated by a small pith ball, and suspended from the upper part of a stem of wood, *s*, which is fitted to a hole in the upper surface of the conductor. An ivory semicircle, or quadrant, *q*, is affixed to the stem, having its centre coinciding with the axis of motion of the rod, for the purpose of measuring the angle of deviation from the perpendicular, which the repulsion of the ball from the stem produces in the moveable rod. The number of degrees which is described by the index, affords some evidence of the quantity of electricity with which the apparatus is charged; though the instrument has obviously no pretensions to being an exact measure of its intensity.

(73.) One of the most delicate instruments for detecting the presence of electricity is that which was invented by Mr. Bennet, and is usually called the *gold-leaf electrometer;* although it is, properly speaking, only an electroscope. It consists (*fig.* 14.) of two

Fig. 14.

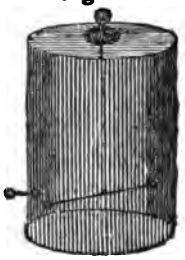


narrow slips of gold leaf, *g*, suspended parallel to each other, in a glass cylinder, which secures it from disturbance by accidental currents of air, and attached to the end of a small metallic tube, which terminates above either in a flat surface, S, of metal, or in a metallic ball. Two slips of tin-foil *t t*, are pasted to the inside of the cylinder, on opposite sides, in a vertical position, and so placed as that the gold leaves may come in contact with them, when their mutual repulsion is sufficiently powerful to make them diverge to that extent. These slips of tin-foil terminate in the foot of the instrument, and thus are in communication with the earth. A very minute charge of electricity communicated to the upper end of the tube, is immediately transmitted to the gold leaves, which are thus made to repel each other; but if the repulsion is such as to make them strike against the tin-foil, their insulation ceases, and their electricity is carried off; and being now rendered neutral, they cease to repel one another, and, collapsing, resume their original position.

(74.) The most perfect electrometer for measuring very small quantities of electricity, is the apparatus contrived by Coulomb, and to which he has given the name of the *torsion balance.* It is represented in its simplest form in *fig.* 15, and consists of a cylindrical glass jar, covered at the top by a circular glass plate, with a hole in its centre. Through this hole a single fibre of

the web of the silk-worm descends nearly to the bottom of the jar, and

Fig. 15.



carries at its lower extremity a transverse needle. This needle consists of either a filament of gum-lac, or a silk thread or piece of straw coated with sealing-wax. At one end it is terminated by a small pith-ball, and at the other by a disc of varnished paper, acting merely as a counterpoise to the ball. The upper end of the silk fibre is affixed to a kind of button having a small index, and capable of being turned round upon a circular plate divided into degrees. One side of the jar is perforated to allow of the insertion of a short horizontal bar, having a small metallic sphere at each of its ends, the one being in the inside and the other on the outside of the jar; and the former being so situated as just to allow the ball of the suspended needle to come in contact with it in the course of its revolution. By turning the button, or the index, the needle may be brought into this, or any other required position with regard to the ball. It is found by experiment that the angle of torsion of the silk fibre is, within a certain range of distance, very nearly in the direct ratio of the force which acts in producing the torsion; and therefore, if the two balls be placed in contact by turning the button, and then similarly electrified, the distance to which they are repelled by the angular motion of the suspended ball, affords a measure of the repulsive force exerted. In like manner, the distance which the suspended ball is made to move when it is attracted by the fixed ball, when the two have opposite electricities, gives accurate measures of the attractive forces. It was by the employment of this apparatus, in a very elaborate series of experiments, that Coulomb was enabled to establish very satisfactorily the exact law of variation, both of the attractive and repulsive forces, arising from electricity, with relation to the distance, which we have already stated.

Chapter V.

Distribution of Electricity.

(75.) It had long been observed, that the quantity of electricity which bodies are capable of receiving, does not follow the proportion of their bulk, but depends principally upon the extent of their surface. It was found, for instance, that a metallic conductor in the form of a globe, or cylinder, contains just as much electricity when hollow, as it does when solid. Hence it was evident that the electricity resides altogether at the surface, or at least does not extend equally throughout the whole mass of the body. But it was only by applying to the theory all the refinements of mathematical investigation, that precise notions could be formed of the exact distribution of the electric fluid in bodies of different shapes. The labours of Cavendish, Coulomb, Poisson, and Ivory, have furnished the means of determining this problem in every case, however complicated; and whenever a comparison has been instituted between the results of experiment and of theory, the most perfect agreement has been found between them. Thus all the phenomena of electricity are found to be in exact conformity with the mechanical consequences of the theory: they can be anticipated with rigorous precision, and can even be reduced to numerical calculation in their minutest details, as well as in their most intricate combinations.

(76.) For the purpose of measuring the proportional quantities of electricity with which different parts of the same, or of different bodies are charged, no instrument is so well fitted as the balance of Coulomb, of which an account has just been given. What peculiarly adapts it for these experiments, is its extreme sensibility, by which the slightest variation in the intensity of the attractive or repulsive force produces a very considerable effect in the movement of the horizontal needle. In some of the experiments related by Coulomb, a force only equal to the 279th of a grain was sufficient to make the needle perform an entire revolution round the

circle: the 360th part of this force, therefore, or less than the 100,000th of a grain, might be estimated by each degree of its angular motion.

In order to apply to the instrument only such forces as it is capable of measuring, and of collecting at the same time from the different parts of bodies such minute quantities of electricity as are exactly proportional to those with which they are themselves charged, Coulomb employed what he calls a *proof plane*, which is simply a small circular disc of gilt paper, *d*, (*fig.* 15,) fixed to the extremity of a very slender cylinder of gum-lac, and thus completely insulated. If we wish, then, to ascertain the proportions in which electricity is distributed on the surfaces or interior of any particular body, we first insulate that body as completely as possible, and impart to it a small quantity of electricity by a spark from the prime conductor. We next touch any of the points on its surface, the electricity of which we may wish to measure, with the little gilt disc, holding it by the other end of its insulating handle; then carrying the plane to the torsion balance, of which the moveable ball has been previously charged with an electricity of the same kind, we bring it for an instant in contact with the fixed ball. We then withdraw it, and the fixed ball being now electrified in the same manner as the moveable one, repels the latter with a force measured by the angle of torsion, at which the moveable ball stops. While the little plane and the balls of the balance remain the same, the division of the electricity between the little plane and the moveable ball preserves the same uniform proportion; and thus the repulsive force which results, and which drives off the moveable ball, is proportional to the quantity of electricity with which the little plane is charged. It has been proved, by a series of well-contrived experiments, that this quantity is exactly proportional to the quantity of electricity which really exists at the point of the body with which it has been placed in contact. By applying the same test and method of admeasurement to various other points of the body we are studying, we may determine the manner in which the electricity is distributed in all its parts; for the method is applicable even to the interior of the body, if we pierce it with a small hole terminating at the part whose electricity we wish to examine, and pass the proof plane into it till it is applied to the bottom of the aperture. Care must be taken, however, in conducting these last experiments, that the proof plane be not suffered to touch any other part of the body except that of which the electricity is to be determined, and not even the sides of the aperture through which it is introduced, as such contact would entirely falsify the result.

The following are among the principal results of these investigations:—

(77.) In a solid body having the form of a perfect sphere, and charged with positive electricity, the whole of the fluid is, in consequence of the repulsion of its own particles, which is everywhere directed from the centre outwards, accumulated in a thin stratum at the very surface of the sphere. If the body be charged with negative electricity, the deficiency of fluid will take place only in the superficial stratum of matter.

(78.) If, instead of being spherical, the body have any other form, the electricity will still be chiefly confined to the surface; and if it have an elongated form, there will be a greater charge in the remoter parts than in those nearer to the middle.

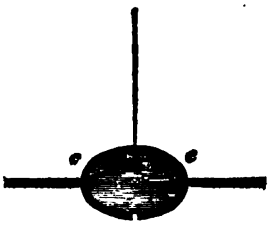
(79.) This result of theory, respecting the limitation of electricity to the mere surface, is confirmed in the most decisive manner by the experiments of Coulomb. A conducting body of the form represented by the section, *fig.* 16,

Fig. 16.

had small pits made in various parts of its surface. They were half an inch in diameter, and some of the most shallow were not depressed more than one-tenth of an inch below the surface. When the body was electrified, and the small proof plane applied in accurate contact to the bottom of these pits and depressions, care being taken that it should not touch their margin, and then applied to the electrometer, no indication of its having received any electricity could be perceived; whereas the contact of the same proof plane with any part of the even surface showed the latter to be strongly electrified.

(80.) The following experiment of Biot's contains also a striking practical illustration of the same truth. Let *a* (*fig.* 17.) represent a section of any spheroid of conducting matter, suspended by a thread which perfectly insulates it. Let *c c* be two caps formed of gilt-

Fig. 17.

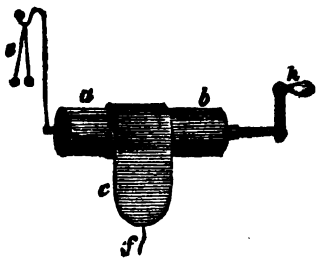


paper, tin-foil, or any conductor, and such that, when united, they accurately fit the surface of the spheroid; and let them be also furnished with insulating handles of gum-lac. Let there be communicated to the ball, *a*, any degree of electricity; and then let the two caps, held by their insulating handles, be carefully applied to its surface. Upon the removal of these caps, it will be found that the whole of the electricity has been abstracted from the spheroid, so that it will no longer affect the most delicate electrometer; whilst the two caps will be found, upon accurate trial, to have acquired precisely the same quantity of electricity which had at first resided in the body *a*.

We may conclude, both from theory and experiment, therefore, that although, strictly speaking, the electricity must reside within the substance of conducting bodies, it extends, in fact, to a depth so small as to be inappreciable by any known methods of observation.

(81.) The effect of an expansion of surface in lessening the intensity of electricity, while its absolute quantity remains the same, is well illustrated by the following experiment mentioned by Biot. *Fig.* 18 represents an insulated cylinder, *a b*, moveable round a horizontal axis, and capable of being turned by an insulating handle *h*. Around the cylinder is coiled a thin lamina of any metal, *c*, the end of which is semicircular, and has attached to it a silk thread *f*. The whole apparatus communicates with an electroscope *e*, formed of two linen threads, each terminating in a pith ball. On communicating a charge of electricity to the cylinder, the threads and balls of the electroscope diverge. Upon taking hold of the silk

Fig. 18.



thread, and unrolling the metallic lamina from the cylinder, the balls gradually collapse; thus indicating a diminution in the intensity of electrical repulsion. If the lamina be sufficiently long, the electrical charge may be spread over so great an extent of surface, as to allow the balls to hang perpendicularly and come in contact. But on winding up the lamina, the intensity of the electricity is restored, and the balls diverge to the same extent as before, allowance being made for the small dissipation of electricity which may have occurred from the contact of the air during the experiment.

(82.) In the case of a long and slender lamina of conducting matter, charged with electricity, Coulomb found that its intensity continued nearly uniform from the middle of the lamina to within a short distance from the ends; at that part it rapidly increased; and at the very extremity it became twice as much as at the middle part. In a circular plate, the electricity is accumulated in much greater quantities at the circumference than about the centre; the intensities being in the proportion of 2.9 to 1: that is, the intensity at the centre is nearly one-third of that at the circumference.

(83.) If the body be an oblong spheroid, arising from the revolution of an ellipse on its greater axis, the thickness of the strata of electricity, or, in other words, its intensity, at the extremities of the two axes, is exactly in the proportion of the respective axes themselves. It thus appears, that if the ellipsoid be much elongated, the intensity must be very feeble at the equator, but very great at the poles. A still more rapid augmentation of the relative

intensity at the extremities takes place in bodies of a cylindric or prismatic form; and the more so as their length bears a greater proportion to their breadth. Coulomb found by experiment that, in a cylinder thirty inches long and two inches in diameter, the intensity of the electricity at the ends was to its intensity at the middle, or at any part more than two inches from the extremity, as 2.3 to 1. Pursuing this train of reasoning, it will lead us to a conclusion of some importance, namely, that if the conducting substance be drawn out into a point, the intensity of the electricity at that point will be exceedingly great; and that the point will accordingly absorb and draw into itself nearly the whole of the electricity that is contained in the body. This vast concentration of electricity is found actually to take place in all points that project beyond the general surface.

Chapter VI.

Transference of Electricity.

(84.) We are next to consider the condition of bodies during the prevalence of those forces which tend to overset the electric equilibrium, over those which tend to preserve it. The pressure exerted by the electric fluid against the non-conducting medium, such as the air, which opposes an obstacle to its escape, is in a ratio compounded of the repulsive force of its own particles at the surface of the stratum of fluid, and of the thickness of that stratum; but as one of these elements is always proportional to the other, the total pressure must, in every point, be proportional to the square of the thickness. If this pressure be less than the resistance, or coercive force, as it has been called, of the air, the electricity is retained; but the moment it exceeds that force, in any one point, the electricity suddenly escapes, just as a fluid confined in a vessel would rush out if it were to burst open a hole in the side of the vessel.

(85.) It is only a certain proportion of the whole quantity of electricity in the conducting body that thus suddenly escapes; but the irruption of it is marked by many very striking phenomena, all indicative of the abruptness and violence with which the change is effected. A sharp snap is heard, accompanied by a vivid spark, and there are evidences of an intense heat being evolved in the line which the electricity takes.

(86.) The passage of the electric fluid through a perfect conductor is unattended with light. Light appears only where there are obstacles in its path by the interposition of imperfect conductors; and such is the velocity with which it is transmitted, that the sparks appear to take place at the very same instant along the whole line of its course. Thus, if a row of small fragments of tin-foil be pasted on a piece of glass, *fig.* 19 and electricity be sent through

Fig. 19.

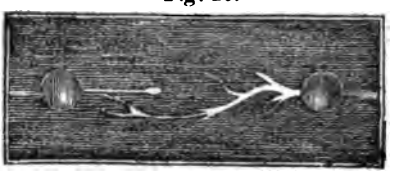
them by connecting one of its ends with the conductor of an electrical machine, while the other end communicates with the ground, it will not be possible to detect any difference of time in the occurrence of the light in the different parts, so that the whole series of luminous points, if sufficiently near, appear, in the dark, like a vivid and continuous line of light. By varying the arrangement of the tin-foil, we may distribute the light in any manner we please, so as to exhibit a brilliant delineation of the figure they represent. Even when conducting bodies appear to be in contact, if the experiment be made in the dark, a spark is generally seen to pass between them, unless the bodies be pressed together with considerable force. Hence, a chain appears luminous at each link, while conveying a charge of electricity.

(87.) The longest and most vivid sparks are obtained between two conductors having a rounded form, and the more so in proportion as they are both portions of spheres of large diameter. This may be exemplified in a common electrical machine, by presenting a metallic ball of large size to that side of the prime conductor which is furthest from the cylinder of the machine. In such cases, however, the electricity being of weaker intensity, the distance between the conducting bodies requisite for the transfer of electricity through the air, or what is termed *the striking distance*, is necessarily small. If the ball is of smaller diameter, or the conductor of a more elongated shape, the electricity at its surface is of higher

intensity, and will therefore pass through a greater extent of air; the spark is in this case of considerable length, appearing as a long streak of fire extending from the conductor to the ball, and instead of being directed towards one point, being distributed to various points throughout a certain extent of the surface of the ball.

Often, when very long, the spark is seen to have an angular or zig-zag course, (see *fig.* 20.) exactly like that of a flash of lightning.—This irregularity

Fig. 20.



is probably occasioned by the fluid darting obliquely in its course to minute conducting particles that are floating in the air, a little removed from the direct line of passage. Even particles of moisture suspended in the air would be sufficient to occasion these deviations. The presence of such particles will account also for the appearance of lateral scintillations, which frequently seem to diverge from the principal stream of electricity. The greater the number of such intermediate conductors, or stepping-stones, as it were, for the electricity, the more readily will the balance between the forces be overset, and the irruption of electric fluid determined.

When the air is either sufficiently moistened, or sufficiently rarefied, the electric fluid passes through it with comparative facility, and its track is indicated by streams of light, probably occasioned by many parallel series of minute sparks passing from particle to particle.

(88.) Electrical light differs in no respect from the light obtained from other sources. Dr. Wollaston found that, when observed through a prism, the ordinary colours arising from the decomposition of light are obtained; but the prevailing tint of colour will vary according to the different substances through which the sparks pass, or to the nature of the surface from which they emanate, or by which they are received. Dr. Brewster found that it is capable of undergoing polarization, either by transmission through a doubly refracting crystal, by reflection at the proper polarizing angle from a polished plane surface, or by oblique refraction through a series of glass plates.

(89.) The brilliancy of the electrical spark is proportional to the conducting power of the bodies between which it passes. When an imperfect conductor, such as wood, is employed, the electric light appears in the form of faint red streams; but metals afford them of great brilliancy. Its colour is subject to variation, from a great number of different circumstances. Sparks passing through balls of wood or ivory, are of a crimson colour; but this depends also upon their position with regard to the surface. If two pointed wires be inserted obliquely and in opposite directions into a piece of soft deal, having their points an inch and a half distant, but penetrating to different depths below the surface, and so that the line joining them is in the direction of the fibres, the sparks passing from the one to the other, will exhibit different colours at different depths; and if one of the points be inserted deeper than the other, all these colours will appear at once, according as the electric light is transmitted at various depths. Electric sparks passing from one polished metallic surface to another are white; but if the finger be presented to an electrified conductor, the sparks obtained are violet. They are green when taken from the surface of silvered leather; yellow when taken from finely powdered charcoal; and of a purple colour when taken from the greater number of imperfect conductors. If one of the bodies between which the spark takes place is a green plant, the light is red; and the same is the case with water or ice. In the vapour of ether green sparks are seen when the eye is placed close to the tube: but they appear reddish when viewed at a considerable distance. Even between the same two metallic conductors the colour may vary from the most brilliant white to the most delicate violet, according to the distance through which the electricity is transmitted, and according to the resistance of the medium which it is compelled to traverse. In exceedingly rarefied air, the colour of the spark is green; in denser air, it acquires a blue tint, and passes to a violet and purple, in proportion as the condensation of the air is increased. Transmitted through other gases, the colour varies according to their density.

In carbonic acid gas, the spark is white and vivid; in hydrogen gas, it is faint and red.

(90.) It should be recollected, in making these experiments, that in proportion as the medium is more rare, its conducting power increases, and a smaller intensity of electricity is required for the production of light. In the ordinary vacuum produced by the air-pump, the passage of electricity is rendered sensible by streams or columns of diffused light occasionally varying in their breadth and intensity, and exhibiting movements which give them a marked resemblance to the coruscations of the Aurora Borealis. After rarefying the air contained in a glass jar, about one foot long and eight inches in diameter, to the 500th part, Mr. Smeaton placed the jar upon a lathe, and caused it to revolve rapidly, whilst at the same time he rubbed it with his hand. A considerable quantity of lambent flame appeared under his hand, variegated with all the colours of the rainbow. The light was steady; but every part of it was constantly changing colours. When a very perfect vacuum is made in a glass cylinder covered with a brass plate, the electric stream will pass between it and the plate of the receiver of the air-pump, in a continued stream of the same size throughout its whole length. If a Torricellian vacuum be formed in the upper portion of a long bent glass tube filled with mercury, and inverted, by placing the legs of the bent tube in separate basins of mercury, when electricity is transmitted through the tube, light is seen to pervade the vacuum in a continued arch of lam bent flame, without the least divergency.

(91.) It was natural to suppose, before sufficient consideration had been bestowed upon the subject, that the light which appears during the passage of electricity, was actually the electric fluid itself, which, at some certain degree of accumulation, was in itself luminous; and such was the notion entertained by the early electricians. But since we know that common atmospheric air becomes luminous by violent compression, and we must also presume that electricity exerts a very sudden and powerful pressure upon the air by its passage through that resisting medium, we are certainly justified in drawing the inference that the same phenomena proceed in both cases from the same cause. Biot has adopted this opinion, which appears to be more consonant with philosophical views of the subject than any other: for it is certain that the whole of the electrical light that appears is not more than what may proceed from the mechanical compression of the air, the vapours, and other constituents of the medium through which the passage of the electricity is effected.

(92.) The sound which accompanies these various modes of transference is subject to corresponding modifications, dependent likewise, no doubt, upon the degree and the suddenness of the impulses given to the air. The full, short, and undivided spark is attended with a loud explosion; the more lengthened spark, with a sharper snap, which becomes more broken and rattling in pro portion to the distance it has to traverse. The luminous streams produced by a succession of minute sparks are scarcely productive of noise, but are accompanied only by a faint rustling sound, like that of a stream of wind through a narrow chink.

(93.) A peculiar odour has sometimes been perceived in the neighbourhood of an electrical machine which has been briskly worked, so as to emit for some time a great number of sparks; and it has been thought to resemble that of phosphorus. This is also probably owing to some unknown chemical decomposition effected by the electricity during its passage through the air.

(94.) We have already had occasion to remark the great increase of intensity which the electric fluid acquires at the extremity of all elongated parts of conducting bodies; and the indefinite augmentation of this intensity which takes place at the apex of all projecting points. This high intensity will necessarily be accompanied with a powerful tendency in the fluid to escape; a circumstance which furnishes a natural and exact explanation of the rapid dis sipation of electricity which takes place from all bodies of a slender and pointed form.

The following experiments illustrate these positions. Let the insulated con ductor of a machine be furnished with a pair of pith-balls, suspended by a fine wire, and charged with either species of electricity; the divergence of the balls will indicate the presence and degree of this electricity. If a metallic rod with a ball at one end be held in the hand,

and the ball presented to the conductor, taking care not to bring it sufficiently near to draw a spark, the balls will be but little affected, and their divergence will continue for a considerable time. But if the rod terminate in a sharp point, instead of a ball, and the point be presented to the conductor at the same distance as the ball was in the former case, the electroscope will immediately collapse, showing that the electrical charge has entirely disappeared: it has, in fact, been rapidly drawn off by the pointed rod. It is quite immaterial to the success of the experiment whether we affix a point to the conductor itself, or whether we present to it a point held in the hand; the escape and dispersion of the electricity being equally promoted by the presence of a point, whether the fluid be given out or absorbed; for it is scarcely necessary to remark that the very same kind of reasoning applies equally to both the positive and negative conditions of electricity.

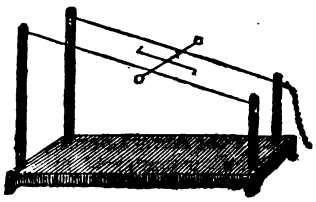
(95.) Currents of air always accompany the discharge of electricity, whether positive or negative, from pointed bodies; for each particle of air, as soon as it has received its electricity from the point, is immediately repelled by the body. These currents tend powerfully to increase the dissipation of the electricity, by bringing in contact with the point a continued succession of particles of air, that are not yet electrified, and are, therefore, ready to receive a charge. Many amusing experiments are founded on this principle. Let two cross wires, (*fig.* 21.) the ends of which terminate in

Fig. 21.

points, bent in a similar direction with respect to the axis, be supported by means of a cap upon a fine point, and electrified by being placed upon the prime conductor of a machine. Each of the points will give off a stream of electricity: this will remove a part of the pressure which the fluid would have exerted on that side if no efflux had taken place; but as the pressure of the fluid on the opposite side of the wire, in the opposite direction, still operates in full force, the wire will be impelled in the direction of that force, that is, in a direction opposite to that of the stream; and this taking place at all the four points, the whole system will revolve backwards with considerable rapidity.

The following is another form in which this experiment may be made. Two wires, (*fig.* 22.) are stretched in

Fig. 22.



the direction of a plane, slightly inclined to the horizon, between four insulating pillars. Across these wires, another wire is made to rest, terminating by small balls at each end, and having a cross wire fixed to it at right angles, with two bent points, as in the former experiment. When this system is electrified, the dispersion of the electricity from the points produces a revolution of the bars, which makes the transverse bar roll up the inclined plane.

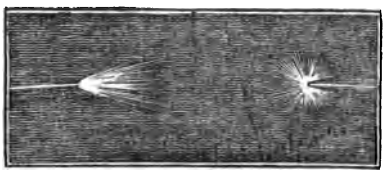
An apparatus consisting of wires terminating in points, and having balls annexed to them to represent the planets, may be constructed so as to revolve when electrified; and thus to imitate the planetary motions. Such an apparatus has been called an electrical orrery.

(96.) It should be observed, however, that a point loses its power of concentrating and dispersing electricity when it is surrounded by other parts of the conducting body which are equally prominent; as when it is placed between two balls, or inclosed in a tube, or when it does not rise above the general surface of the body. The effect of one point is much diminished even by the vicinity of another point; so that if several points placed near each other be presented to the conductor, the electricity is drawn off much less rapidly, and will be transferred by sparks instead of forming a continued stream.

(97.) When the transfer of electricity takes place between smooth surfaces of a certain extent, no difference can be perceived in the nature and appearance of the spark, whichever be the position of the negative surface. But in the passage of electricity through points,

the effect is considerably modified by the species of electricity with which the bodies are charged; or, in other words, by the direction in which the fluid moves. When the electric fluid is escaping out of a pointed conductor, the luminous appearance is that of diverging streams, as represented in *fig.* 23; forming what is termed a *pencil of light*, and

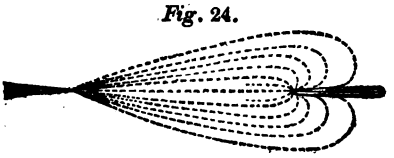
Fig. 23.



resembling the filaments of a brush. When, on the contrary, the electric fluid is entering into the pointed body, the light is much more concentrated at the point itself, having a resemblance to a *star*, in which, if any streams appear, they are disposed like radii, and equally so in all directions. An approach to these different modifications may be remarked when sparks pass between balls of small diameter, especially if the charge is high. Thus the direction of the lateral ramifications sent out from the principal line, in the branched spark, *fig.* 20, is from the positive to the negative surface.

(98.) In describing the above appearances, we have, as usual, referred to the hypothesis of Franklin: but if we adopt that of the two electricities, we have only to consider the appearance of the pencil of light as arising from the double current of the vitreous electricity issuing from the point, and of the resinous electricity passing into it: while the star will be the effect of the irruption of the resinous, and the absorption of the vitreous electricities. But this remarkable difference in the phenomena produced, according to the particular species of electricity with which the point is charged, has always been urged as a convincing argument in favour of the Franklinian theory. They appear very strongly to indicate the emanation of some material fluid from the positive, and its reception by the negative point. The diverging lines on the one side, and their inflections on the other, represent exactly the paths of particles flowing out as from a pipe, and urged forwards by a force which gives them such a projectile velocity as to prevent their spreading out beyond a certain distance from the direct line of projection. But this very velocity will carry the particles that happen to have deviated most, somewhat beyond the point to which they are attracted: while the attraction to this latter point will tend to deflect them from the line of their path, and gradually turn them back, so that they will arrive at the point of attraction by very different paths, and some even by a retrograde motion. Hence, while in the first case they form a diverging cone of rays, in the latter they must be distributed on all sides of the point like the rays of a star. The annexed diagram, *fig.* 24, will sufficiently illustrate this explanation by

Fig. 24.



representing the supposed course of the particles of electric fluid, passing through the air from the positive to the negative point. What weight the argument derived from this phenomenon may be allowed in deciding the question, will be discussed in the sequel.

(99.) The difference which we have now described in these two appearances, may be employed, on many occasions, as a useful criterion of the species of electricity, at least, which is passing from one conductor to another, if not of the absolute direction of its motion. For, if a needle be presented to an electrified body, the appearance of a star on the needle will show that the electricity of that body is positive; while, on the contrary, a luminous brush on the needle will indicate that the body is negative.

(100.) The influence of a point projecting a short distance from the surface of a body, is greater when that body is negative than when it is positive. Hence, a spark is more readily obtained in the latter case than in the former.

On this principle an instrument has been invented by Mr. Nicholson for distinguishing the negative from the positive electricity. It consists simply of two metallic balls fixed at the ends of two curved rods of glass, and moveable like branches on a joint, so as to admit of the balls being placed at different

distances from each other, when held by a handle proceeding from the joint. A short point projects from one of the balls on the side adjacent to the other ball; and this point affords a spark at a shorter distance when positively, than when negatively electrified.

Chapter VII.

Development of the Law of Induction.

(101.) We have next to trace the consequences of that important law of electricity which has been called the Law of Induction.

Active electricity existing in any substance tends always to induce the opposite electrical state in the bodies that are near it. Now it is impossible, as we have already seen, to induce one electrical state in any body without at the same time producing the opposite state in the same body, or in the one which is immediately contiguous. According to the simpler theory, the accumulation of electricity in any one part can be effected in no other way than by withdrawing it from another part, nor can it be abstracted from the one without being received by another; so that there is always an equal degree of negative as of positive electricity, and *vice versâ*, in every case. According to the more complex theory, if we decompose the natural electricities residing in any body, we must at the same moment obtain equal quantities of both the vitreous and resinous electricities. It follows, therefore, that if the bodies subjected to the inductive influence are non-conductors, although the tendency to produce the opposite electricity still exists, yet in consequence of the immobility of the fluid, it can produce no visible change. In proportion as the body opposes less resistance to the passage of electricity, the operation of the disturbing force becomes sensible; and in order to fix our ideas, let us first take the case of a positively charged electric, acting by induction on an insulated conducting body. The redundant fluid in the former will tend to repel all the fluid contained in the latter: a portion of this fluid will, therefore, be driven from the side adjacent to the first body, towards the remoter side. The adjacent side will thus be rendered negative; the remote side, positive. But this will take place to a certain extent only: for there is a limit at which the repulsion of the fluid accumulated at the remote end, will just balance the repulsion of the fluid in the electric, added to the attraction of the under-saturated matter, in the near end; and when this limit has been attained, the flow of electric fluid from the near to the remote end of the body will cease, and an equilibrium will be established.

(102.) Experiment shows the perfect coincidence of theory with the actual fact. Let a cylinder of metal, NP, (see *fig.* 25,) of some length, with rounded ends, and furnished in different parts

Fig. 25.

with pairs of suspended pith-balls, to serve as electroscopes, being previously insulated, be placed in the vicinity of an electrified globe of glass, E, taking care that it be not sufficiently near to receive any quantity of electricity by transference.

We shall find that every pair of balls, except those situated in a particular plane M*m*, about the middle of the cylinder, will immediately diverge, indicating the electrical states of the parts from which they are suspended. Those at either extremity of the body, *n*, *p*, diverge the most; and the divergence diminishes as we approach the middle plane before mentioned, at which the body is in the natural or neutral state. The position of this plane of neutrality, M*m*, varies according to the distance of the electric, and the relation which that distance bears to the length of the body itself. If we further examine the species of electricity residing in the different parts, we shall find it to be negative in all the parts nearer to the electric than the neutral plane, and positive in all those more remote. We may ascertain with much greater accuracy these electrical states by the employment of the proof plane and electrometer of Coulomb, than by the pith-balls; and the results are then found to correspond, with the most rigorous precision, with the deductions from the theory of electrical action.

(103.) These effects, it should be remarked, are simply the result of the action of electricity at a distance; for they depend upon no other circumstance.

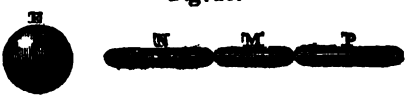
They take place in an equal degree whatever substance be interposed between the bodies which are exerting this action on one another, provided the interposed substance undergoes no change in its own electrical state; a condition which is fulfilled in electrics only. Thus, induction will take place just as effectually through a plate of glass, as if no such substance had intervened.

(104.) Let us now suppose that the acting body, E, is, instead of an electric, a conducting body, a globe of metal, for example, charged with positive electricity. The primary effects of this globe on the cylinder will be the same as in the former case; but the electrical state which the globe has induced on the cylinder will re-act upon its own electricity. The negative electricity, that is, the under-saturated matter at the nearer end of the cylinder N, exerts a tendency to induce positive electricity in the globe, and more especially upon the adjacent side, F: that is, it will tend, by its attraction for the fluid, to draw it to that side, and thus render it still more highly positive than it was before. This can only be done at the expense of the other side, O, from which the fluid must be taken, and which is, therefore, rendered less charged with fluid, that is, less positive than before. But this new distribution of the electric fluid in the globe, by increasing the positive state of the side, F, next to the cylinder, tends to augment its inductive influence on the fluid in the cylinder; that is, to drive an additional quantity of fluid from the negative to the positive end. This is followed, in its turn, by a corresponding reaction on the globe, and so on, constituting a series of smaller adjustments, until a perfect equilibrium is established in every part. When this has been attained, the electrical states will, it is evident, be of the same kind as those consequent upon the immediate actions, though somewhat increased in intensity by the series of reactions.

The following experiment is a practical illustration of the preceding reasoning. Furnish the metallic globe with electroscopes on its opposite surfaces; when the globe is insulated and alone, any electricity communicated to it will diffuse itself equally over the surface, and both the electroscopes will diverge equally But no sooner do we bring near to it a conducting body, than the balls of the electroscope at the side most distant from that body begin to collapse, while those at the nearer side diverge to a greater degree than before; thus showing the nature of the reflex operation of the induced electricity of the conductor upon the body from which the induction originated.

(105.) It should be recollected that in all the changes we have thus traced as the effects of induction, there has been no transfer of electricity from either of the bodies to the other; as was sufficiently proved, indeed, by their taking place equally if a plate of glass be interposed. Another proof is afforded by the circumstance that the mere removal of the bodies to a distance from one another, is sufficient to restore each of them to their original state. The globe remains as positively electrified as before; the cylinder returns to its condition of perfect neutrality; nothing has been lost, and nothing gained on either side. The experiment may be repeated as often as we please, without any variation in the phenomena. But this would not be the case if the cylinder were divided in the middle, and one or both of the parts were removed separately, while they still remained under the influence of the globe. The return of the electric fluid from the positive to the negative end being thus prevented, each part will retain, after its separation, the electricity which had been induced upon it. The nearer portion will remain negative; the remoter portion, positive. If the division had been in three parts, the middle part only would have been neutral. The experiment may be made by joining two or more conductors endwise, as shown in *fig.* 26, so that they

Fig. 26.



may act as a single conductor when placed near to the electrified globe, and after induction has thus been produced, removing them separately, and examining their electrical states. If E be positive, N will be found negative, P positive, and M neutral.

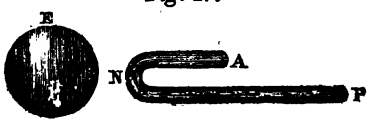
(106.) Another modification of effect will take place when an insulated conductor, rendered electrical at both ends by induction, is made to communicate with another conductor. Let us first suppose that a long metallic conductor

is brought into contact with the remote end of the first cylinder P, (*fig.* 25), which has been rendered positive by induction. The fluid accumulated at this end will now pass into the conductor, and will remove to the most distant part of the conductor. The transit will now take place before actual contact, and will be manifested by the appearance of a spark when the bodies are brought within the striking distance. The removal of this fluid to a greater distance will occasion a disturbance in the equilibrium that had before been established. The repulsion which that fluid had excited, and which had contributed to prevent any more fluid from being propelled from the negative end N, is now considerably weakened by the greater distance at which it acts; and more fluid will leave the negative end, which end will consequently become more highly negative. This change of distribution will again occasion a further effect, by its reaction on the fluid in the globe whence the action originally proceeded; and another series of changes and adjustments will follow, until a new condition of equilibrium takes place, and then the fluid will be at rest.

(107.) Thus we learn that the effects of induction on a conductor are augmented by increasing its length; they would, therefore, be greatest of all, if we could give it infinite length: but the same condition is attainable by placing the conductor in communication with the earth, which will accordingly carry off all the fluid which the electrified body is capable of expelling from the nearest end. Accordingly, if we touch with the finger, or with a metallic rod held in the hand, the remote end of an insulated conductor under the influence of induction, we obtain a spark, more or less vivid according to the intensity of the electricity so induced; and the conductor so touched has now only one kind of electricity, namely, the one opposite to that of the electrified body which is acting upon it. The part touched is brought into a state, in which it appears to be neutral as long as it remains in the vicinity of the electrified body; because the actions of the redundant fluid, and unsaturated matter in the two bodies, exactly balance one another. But it all the while really contains less fluid than its natural share, in consequence of the repulsive tendency of the fluid in the body which produces the induction; and this negative state will readily become active, if the conductor that has been touched be again insulated, and then removed from the influence of the former. This peculiar condition of a body, in which its parts are really undercharged or overcharged with fluid, although, from the action of electrical forces derived from bodies in its vicinity, a state of equilibrium is established, and no visible effect results, has been denominated by Biot, ***disguised electricity***.

(108.) It is also worthy of remark, that if the communication between the insulated conductor and another longer conductor, or the earth itself, be made at either end of the former, the same effect will result, and the electric fluid accumulated at its remote end will be carried off by the longer conductor, although, it will have, in one case, to pass round through the end nearest to the body which repels it. The operation which here takes place may be illustrated by the motion of a fluid in a syphon. A repulsive force is acting upon the fluid, both in the shorter and the longer column; but with regard to the motion of the fluid in the bent channel the one force is in opposition to the other, and the tendency of the fluid in the longer column prevailing over that in the shorter, will draw off the latter, round the bend of the supposed syphon. Thus in the bent conductor A N P (*fig.* 27,), the repulsion exerted by the fluid in E for that in the longer column N P,

Fig. 27.



being greater than its repulsion for that in the shorter column N A, the fluid in A will be carried over the bend N, notwithstanding its tendency to move from N towards A.

(109.) We have hitherto supposed the acting body to be positively electrified; but precisely the same effects would happen with regard to degree, although opposite as to the species of electricity, if it had been negatively electrified: and the same explanations will in every respect apply, with the requisite substitution of the terms negative for positive, and of attraction for repulsion, and *vice versâ*. A little reflection will also easily show the application of the

theory of the double electricities to explain the same phenomena.

(110.) Another consequence of the induction of electricity must not be overlooked, namely, that the bodies between which it takes place, necessarily attract one another: for the action of the adjacent sides F and N (*fig.* 25), which are brought into opposite electrical states, is greater than the action of those sides which are in the same electrical states, F and P, and which are more distant: hence the attractive force always exceeds the repulsive. We have already seen that this circumstance sufficiently explains the fact that conducting bodies, previously neutral, are attracted by electrified bodies. Another fact, which appears more singular, and which cannot be accounted for on any other principle, is also a direct consequence of the law of induction. If a small body weakly electrified, be placed at a distance from another and a larger body, more highly charged with the same species of electricity, it will, as usual, be repelled; but there is a certain distance within which if it be brought, attraction will take place, instead of repulsion. This happens in consequence of the inductive influence producing so great a change in the distribution of electricity, as to give a preponderance to the attractive forces of the adjacent parts of the two bodies, over the repulsive forces that take place in the other parts, and which would have alone acted if the fluid had been immoveable.

(111.) From the principles now laid down, it will be easy to understand how induction may operate through a succession of conductors, which are all of them insulated, except the last; and which are separated from each other by distances greater than that at which a transfer of electricity would take place. If, under such circumstances, the first be electrified, alternate states of opposite electricities will be produced in the two ends of each conductor in succession. In all the ends nearest to the first body, the electricity will be of the opposite kind to that with which the first has been charged; in the other ends it will be of the same kind as that of the first body. The vicinity of these opposite electricities will tend powerfully to retain them in that condition, and will diminish their electric action on surrounding bodies. A large portion of the electricities so arranged and retained, is, therefore, in the condition designated by the term *disguised electricity*.

(112.) In proportion as the interruptions to the continuity of the line of conductors are more numerous, the more nearly will such a system approach to the condition of an imperfectly conducting body. The same principle admits of being extended, with some modifications indeed, to the constitution of electries themselves, as we shall have occasion to notice in the sequel.

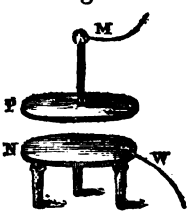
Chapter VIII.

Accumulation of Electricity by Induction.

(113.) The most important application of the principle of induction is that by which a vast accumulation of electricity is obtained in a small space, while its intensity, or tendency to escape, is at the same time rendered exceedingly small. This condition exactly corresponds to that which has been termed *disguised electricity*.

(114.) Let two circular metallic plates P and N (*fig.* 28), be placed the one immediately over the other, but separated by a non-conducting medium, such as the air, or, what is still better, a plate of glass. Let the upper one P, commu-

Fig. 28.



nicate, by a wire M, with the prime conductor of the electrical machine; and let the lower one N, be insulated by resting upon three glass supporters. Let P be charged with a certain quantity of electric fluid. The fluid naturally contained in N, will be repelled by the fluid in P, and will quit the upper surface of N in order to occupy its lower surface. When this change has taken place, let N be touched by a wire W, establishing a communication between it and the ground. All the fluid which was accumulated in the lower surface of N, will be carried off by the wire, and the whole plate will thus be negative, or undercharged with fluid. The

redundant matter in N will, by its attraction for the fluid, draw more of it into the upper plate, which will be supplied from the conductor of the machine through the wire M; and such an additional quantity will be accumulated in P, as will balance the increased attraction of the matter in N, and maintain it at the same intensity as the fluid in the prime conductor. That this is what really happens will be rendered evident by placing an electroscope upon the prime conductor; for the moment the plate N communicates with the ground, the balls of the electroscope collapse, showing that the intensity of the fluid in the prime conductor is suddenly reduced by the great quantity that has been absorbed by the plate P. The machine must now again be set in motion, in order to supply the electricity which has been thus abstracted from the conductor. The operation of each plate on the other may be considered as that of increasing its electrical capacity, or of rendering a large proportion of its electricity latent or disguised.

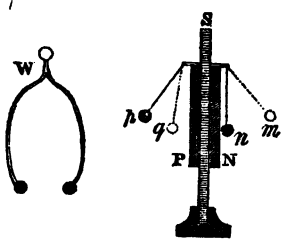
(115.) It is evident that the quantity of electric fluid driven out of the lower plate by the action of the fluid in the upper one, can never be quite equal to that of the fluid with which the upper one is itself charged, and the difference will be greater in proportion to the distance of the plates. When they are very close to each other, these two quantities approach very near to an equality; and this circumstance it was that misled Franklin into the belief that they were actually equal.

(116.) The capacity for accumulating electricity corresponding to a given intensity in the upper plate depends upon the distance between the plates, provided always that the intervening electric opposes a sufficient obstacle to the direct transfer of the electricity from the one to the other; and is in some inverse ratio to that distance. The lower plate, N, which communicates with the ground by the wire W, although strongly negative, is rendered, by the vicinity of the fluid in the upper plate P, neutral with respect to fluid in the wire W: that is, the attraction of its unsaturated matter, although nearer, is exactly balanced by the repulsion of the redundant fluid in the upper plate, which, although really stronger, is, from the greater distance at which it acts, only equal to the former. With reference to fluid in the wire M, however, the action of the redundant fluid in P, is not balanced by that of the unsaturated matter in N, which latter is both weaker in itself and more distant. Thus, while N is neutral with respect to the conductors which touch it, P is in a slight degree active, in consequence of this small preponderance of force, and a portion of its fluid tends to escape. Hence, if N be again insulated, by removing the wire W, and the wire M be now made to communicate with the ground, this portion of the fluid in P will pass off by it; but not any larger quantity, for the remaining portion is retained by the attraction of the unsaturated matter in N. P is, by this loss, rendered neutral, as N had before been, and it now no longer acts on the fluid beyond it in M. The influence of P on that fluid is greater than that of N in respect to its greater vicinity, but less in as far as regards the intensity of action, and the compensation is exact. But under these circumstances, N, which was before neutral, becomes in its turn active, and now that the repulsion of the fluid in P is diminished, will absorb a certain quantity of the fluid as soon as it is touched by W, after P has been again insulated. By this contact, N is again restored to the neutral state, a fresh portion of fluid in P is released from the attraction of N, and P is again active. By repeating these alternate contacts a sufficient number of times, we gradually deprive the plates of their whole charge of electricity; alternately imparting small portions to the negative plate, and taking away the like portions from the positive one, until they are both brought to their natural unelectrified state. The quantities of fluid which are thus successively added and abstracted were found, by the calculations of Laplace, to be in geometrical progression.

(117.) The most convenient mode of obtaining the accumulated electricity arising from induction is by the employment of *coated glass*, that is, of a plate of glass, on each side of which is pasted a sheet or coating of tin-foil. Care must be taken to leave a sufficient margin of glass uncovered by the metal, for preventing the transfer of electricity from the one coating to the other round the edge of the glass; and all sharp angles, or ragged edges in the coatings, should be avoided, as they have a great tendency to dissipate the charge.

(118.) The following experiment of Professor Richman, (the philosopher who fell a sacrifice to his zeal for electrical science by a stroke of lightning from his apparatus,) is very instructive. Let a pane of glass placed vertically, and seen edgewise in *fig.* 29, be coated on both sides, and furnished with two

Fig. 29.



small electroscopes, *p*, *n*, consisting of two pith-balls, one attached to each of the coatings. Let the coating P be charged positively, while the coating N is made to communicate with the ground. The electroscope *p* will stand out from the plate, and *n* will hang down close to its coating, as long as N communicates with the ground. But in proportion as P loses electricity by gradual dissipation in the air, the ball *p* will gradually, but very slowly descend. If we now insulate N, *p* will fall down at first very speedily, and then more slowly, till it reaches *q*, about half its first elevation. The ball *n* will at the same time rise to nearly the same height; the angle between the two electroscopes continuing nearly the same as at first. When *n* has ceased to rise, both balls will very slowly descend, till the charge is lost by dissipation. If we touch N during this descent, *n* will immediately fall down, and *p* will as suddenly rise nearly as much; the angle between the electroscopes continuing nearly the same. Remove the finger from N, and *p* will fall, and *n* rise, to nearly their former places; and the slow descent of both will again recommence. The same thing will happen if we touch P, *p* will fall down close to the plate, and *n* will rise to *m*, and so on; and this alternate touching of the coatings may be repeated some hundreds of times before the plate is entirely discharged. If we suspend a crooked wire, bent, as shewn at W, (*fig.* 29,) having two pith-balls, from an insulated point, *s*, above the plates, it will vibrate with great rapidity, the balls striking the coatings alternately, and thus restoring the equilibrium by steps; each contact being attended by a spark.

(119.) If, instead of this gradual discharge, a direct communication is made between the two coatings by a metallic wire extending from the one to the other, the whole of the electric fluid which was accumulated in the positive coating rushes with a sudden and violent impetus along the conductor, and passes into the negative coating, thus at once restoring an almost complete equilibrium, and rendering every part very nearly, though not absolutely, neutral; for as there must always be some slight difference in the quantity of electrical charge in the two coatings, where one of them is in communication with the ground, there must always be a certain excess, however minute, of electricity, after the balance has been struck.

(120.) This sudden transfer of a large quantity of accumulated electricity is a real explosion; it gives rise to a vivid flash of light, corresponding in intensity to the magnitude of the charge. The effect of its transmission is much greater than that of the simple charge of the prime conductor of the machine; for while the latter gives a spark only, the former imparts what is called *an electric shock*, and the sensation it produces when passing through any part of the body is of a peculiar kind. We shall describe their effects in a future chapter; at present we must confine our attention to the purely electrical conditions of the phenomenon.

(121.) The presence of the coating is not absolutely essential to the charge and discharge for the two surfaces of the glass plate; for if the glass be furnished with moveable coatings, and charged in the usual manner, upon removing the coatings (taking care that they be touched only by electrics,) the greater part of the electricity will be found to have attached itself to the surfaces of the glass plate, where they are retained by their mutual inductive influence. In this state the charged plate of glass may be gradually discharged by making a communication between its several parts in succession. It cannot be discharged at once, for want of a common intermedium for the simultaneous transference of the electricity of the different parts of the surface. But if this be supplied by replacing the former coatings, or adding new ones

the complete discharge may be effected as before.

(122.) By peculiar management a charge may be given to a plate of glass independently of any coating whatever. For this purpose, it must be held by one corner, and passed before a ball, connected with the prime conductor of a machine, so that it may successively come in contact with every part of the middle of the plate of glass, while the finger, or any conducting body communicating with the ground, is held opposite to it on the other side. Thus the glass will be charged, and will be in the same state as the glass from which the coatings had been removed.

(123.) We often find, a short time after the discharge of coated glass, that it has acquired spontaneously a small charge, producing a faint spark when a second communication is made between the coatings by the discharging wire. This, which is called the *residual* charge, arises from two causes: first, a portion of the electricity adheres to the uncoated surface of the glass: and secondly, another part has penetrated from the coating for some little depth below its surface. Both these portions slowly return to the coatings after they have been deprived of their original charge, and give it a fresh charge. When a very large extent of coated glass is employed, this residual charge may even amount to a considerable quantity, and the experimenter should be cautious not to expose himself to the shock which he might thus receive, if he inadvertently touched the apparatus before he had properly discharged it. That charges are capable of penetrating even through the entire thickness of the glass is proved by the curious fact, that a coated, cylindrical jar may be discharged merely by keeping up for a sufficient time a continuance of the minute vibrations excited by rubbing it with the finger, or by making it ring. A discharge may also be effected by heating the glass, which renders it a conductor of electricity.

(124.) The most convenient form for coated glass for experimental purposes, is that of a cylinder or jar. In the earlier periods of electrical research, jars were filled with water, mercury, or iron filings, which furnished the interior coating, while the exterior coating was supplied either by water, in which the jar was immersed, or by the hand of the operator, who for that purpose grasped the outside of the jar: a rod of metal was employed to communicate the charge from the prime conductor of the machine to the inner coating. On making a communication between the exterior and interior coatings, by means of a circuit of conducting substances, the discharge took place, and the shock made to pass through the circuit thus formed. This instrument having been made known principally through the experiments of Kleist, Cuneus, and Muschenbroeck, at Leyden, the name of the *Leyden phial*, or *jar*, was generally applied to it. It is at present constructed as shewn in *fig.* 30, by applying coatings of tin-foil on both sides of the jar or bottle, leaving a sufficient space uncovered at its upper part to secure it from the risk of a spontaneous discharge, which might take place if the coatings were not separated by a sufficient interval. A metallic rod, rising two or three inches above the jar, and terminating at the top in a brass ball, which is often called the *knob* of the jar, is made to descend through the cover, till it touches the interior coating. It is through this rod that the charge of electricity is conveyed to the inner coating, while the outer coating is made to communicate with the ground. We have already seen, that if this last condition be not observed, the inner coating can receive no charge, and only a feeble spark will pass from the conductor to the knob.

Fig. 30.

(125.) The outer coating may be made to communicate with the ground by holding it in the hand; and on presenting the knob of the jar to the prime conductor when the machine is in motion, a succession of sparks will pass between them, while at the same time nearly an equal quantity of electricity will be passing out from the exterior coating, through the body of the person

who holds it, to the ground. If, instead of this, the jar be placed on an insulating stand, and a ball of metal, or the knuckle of the finger, be held near the outside of the jar, we have evidence of the escape of the electricity from the latter by a succession of sparks simultaneous with those that occur between the prime conductor and the knob of the jar.

(126.) If, instead of touching the outer coating of a jar supported on an insulating stand, we bring into contact with it the knob of a second jar, of which the outer coating communicates with the ground, as shewn in *fig.* 31,

Fig. 31.

the electricity which is expelled from the outer coating of the first jar passes into the inner coating of the second jar, and thus both jars are charged. Thus may charges be given to a succession of jars, so placed as that the inner coating of each shall communicate with the outer coating of the one that precedes it in the series; taking care that the outer coating of the last jar communicates with the ground. All the jars will be found to be charged in a similar manner. It is evident, however, that the charge must diminish in intensity as it is conveyed from each jar to the next, because the quantity of electricity which is expelled from the exterior is never quite equal to that which passes into the interior.

(127.) For the sake of greater distinctness we have all along supposed the interior of the jar to be charged with positive electricity, but the very same effect would take place if the knob of the jar were charged negatively by communication with the negative conductor. A similar change in the electrical state of the coatings would result from placing the jar on an insulating stand, and then forming a communication between the outer coating and the prime conductor, while the knob is made to communicate with the ground. The only difference is, that the outer coating would then be active and the inner one neutral; but these conditions would again be reversed as soon as the knob was disconnected with the ground, and the outer coating touched with the hand.

(128.) If two jars, the one charged positively, the other negatively, be placed on two separate insulating stands, and their knobs then connected by a conductor, which is itself insulated, no explosion will take place, although the two coatings, which are thus brought into communication, are in opposite electrical states. But if the two outer coatings be at the same time connected, an explosion will take place, and both jars will be discharged.

(129.) Since the susceptibility of receiving a charge depends upon the proximity of the metallic surfaces, while the passage of the electricity from the one to the other is interrupted by the interposition of a non-conducting substance, it is evident that, in the construction of the Leyden jar, the thickness of the glass is an important consideration. The thinner the glass, the greater will be the power of taking a charge; but the power of retaining the charge will be less, on account of the diminished resistance which the glass will afford to the passage of the electricity through it. If the charge be higher than what the jar will bear, the glass will be broken by the violence with which the electricity forces a passage through its substance. Muscovy talc, even in very thin laminæ, resists much better than glass, and is, therefore, capable of receiving and of retaining a much higher charge. Another limit to the charge which a jar is capable of retaining, arises from the liability of the electricity to pass from one coating to the other, round the edges of the glass.

(130.) These spontaneous discharges, as they are called, are facilitated by the deposition of moisture on the glass, forming a chain of conducting particles in the very line which the electricity has a strong tendency to take. Hence, it is a requisite precaution to keep the apparatus in as dry a state as possible; and the deposition of moisture may be guarded against most effectually by covering the uncoated part of the glass with a layer of sealing-wax, or other

resinous varnish. The liquid should be applied with a flat, camel-hair pencil, the glass being previously warmed.

On the other hand, it is a curious circumstance, that there is a degree of humidity in the inside of the jar, not only compatible with a high charge, but which even contributes to retain it. This effect was accidentally observed by Mr. Brooke, and afterwards by Mr. Cuthbertson, who states that a jar will take a much greater charge, namely, one-third more, if its inside be considerably damped by blowing into it with the mouth through a tube reaching to the bottom. The explanation of this remarkable fact has been given by Professor Robison on the principles formerly explained, namely, that there is no electric intensity so great, but that it may be insulated by the least imperfect conductor, provided the latter be long enough, and so constituted as that the intensity of the electricity it contains shall diminish by sufficiently gentle gradations. An uniform dampness, indeed, will not do this; but it will diminish the abruptness of the variations of intensity, and thus give security against a spontaneous discharge. A similar protection against the breaking of the glass is afforded by placing a layer of paper between the glass and the tin-foil, and making it extend also an inch beyond the coating.

(131.) Glass balloons of a spherical shape, being of more uniform thickness than jars, would be much preferable for the construction of an apparatus of this kind, were it possible to apply an uniform coating to the inside. Professor Robison recommends the following construction for a portable jar, which he found to answer exceedingly well. A long-necked phial was made of sheet tin, and then coated entirely on the outside with fine sealing-wax, one thirtieth of an inch thick. The sealing-wax was then coated with tin-foil, all but the neck. It is evident, that the wax here acts the part of the glass in the common jar, the tin plate corresponding to the inner coating and wire, and the tin-foil to the outer coating. The dissipation is almost nothing if the neck be very small; and it only requires a little caution to avoid bursting by too high a charge. Even this may be prevented by coating the sealing-wax so near to the end of the neck, that a spontaneous discharge must happen before the accumulation is too great. Alternate layers of tin-foil and hard varnish form also a very compendious battery. It admits of a surprising accumulation, without shewing any vivid electricity; but it must be used with more caution, lest it should be spoiled by a spontaneous discharge, in which case we cannot discover where the flaw has happened, and the whole is rendered useless.

(132.) By combining together a sufficient number of jars we are able to accumulate an enormous quantity of electricity: for this purpose all the interior coatings of the jars must be made to communicate by metallic rods, and a similar union must be established among the exterior coatings. When thus arranged, the whole series may be charged, as if they formed but one jar; and the whole of the accumulated electricity may be transferred from one system of coatings to the other, by a general and simultaneous discharge. Such a combination of jars is called an *Electrical Battery*.

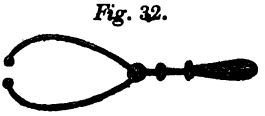
(133.) It is evident, that an apparatus of this kind, consisting of a great number of parts, must be more liable to derangement than a single jar: for if any one of the jars should happen to break by a spontaneous explosion, the whole battery would be rendered useless, until the broken jar be removed. It is prudent, therefore, to secure the adjacent jars from actual contact, by fixing them in a box having thin partitions; the coated bottoms of the jars resting on a trellis of wire, or on a sheet of tin-foil, which may establish a general communication between them; while the rods from the interior coatings are connected above by cross wires, having balls at their extremities in order to obviate the dissipation of the electricity. On the other hand, by limiting the communications to a certain number of jars, we have it in our power to charge only a part of the battery, without employing the whole.

Chapter IX.

Management of Electrical Jars and Batteries.

(134.) For the purpose of making the direct communication between the inner and outer coating of a jar or battery, by which a discharge is effected; the instrument shown in *fig.* 32, and which is

Fig. 32.



called the *Discharging Rod* or *Jointed Discharger*, may be conveniently employed. It consists of two bent metallic rods, terminated at one end by brass balls, and connected at the other by a joint, which is fixed to the end of a glass handle, and which, acting like a pair of compasses, allows of the balls being separated at different distances. When opened to the proper degree, one of the balls is made to touch the exterior coating, and the other ball is then quickly brought into contact with the knob of the jar, as represented in *fig.* 33, or with

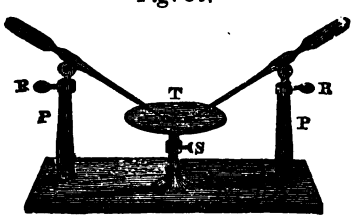
Fig. 33.

any part of the system of the interior coatings, and thus a discharge is effected; while the glass handle secures the person holding it from the effects of the shock.

(135.) If we wish to send the whole charge of electricity through any particular substance which may be the subject of experiment, we must so arrange the connecting conductors, as that the substance shall form a necessary part of the *circuit of the electricity*, as it is termed. With this view, we must place it between two good conductors, one of which is in communication with the outer coating; and the circuit may then be completed by connecting the other conductor with the inner coating by means of a discharging rod, to one branch of which, if necessary, a flexible chain may be added.

(136.) In order to direct the charge with more certainty and precision, an apparatus, called the *Universal Discharger*, was contrived by Mr. Henley, and is represented in *fig.* 34. It con-

Fig. 34.



sists of a wooden stand with a socket fixed in its centre, to which may be occasionally adapted a small table T, having a piece of ivory (which is a non-conductor) inlaid on its surface. This table may be raised and kept at the proper height by means of a screw S. Two glass pillars P, P are cemented into the wooden stand. On the top of each of these pillars is fitted a brass cap, having a ring R attached to it, and containing a joint, moving both vertically and horizontally, and carrying on its upper part a spring tube, admitting a brass rod to slide through it. Each of these rods is terminated, at one end, either by a ball, a point, or a pair of forceps, and is furnished at the other extremity with a handle of solid glass. The body through which the charge is intended to be sent, is placed on the table, and the sliding rods, which are moveable in every direction, are then, by means of their insulating handles, brought in contact with the opposite sides, and one of the brass caps being first connected with the outside of the jar or battery, the other may be brought in communication with the inner coatings, by means of the discharging rod above described. For some experiments it is more convenient to fix the substance, on which the experiment is to be made, in a mahogany frame, consisting of two boards, which can be pressed together by screws, and which may then be substituted for the table T. In either of these ways the charge can be directed through any part of the substance with the greatest accuracy.

(137.) The quantities of electricity which can be accumulated in any given extent of coated glass, are in the inverse proportion to the thickness of the glass. Different jars or batteries, therefore, will, according to the thinness of their sides, and the quantity of coated surface they contain, have different capacities of holding charges of electricity. But in any given instrument of this kind, the quantity of the charge communicated to it by a machine may be measured by the intensity of the electricity in the prime conductor, which communicates with the interior coating. Some estimate of the intensity may be obtained by the employment of Henley's quadrant electrometer already described, (§ 72,) the index of which rises very slowly while the battery is charging, till it reaches a certain elevation, corresponding to the capacity of the battery. If

the electricity be accumulated beyond this limit, a spontaneous discharge takes place, and the process must then be renewed in order to obtain a full charge. It is more prudent, however, to stop before this degree of accumulation is attained: and one great advantage of Henley's electrometer is, that it shows us the progress of the charge, and how far we may proceed with safety.

(138.) But the most effectual security against fracture from a spontaneous discharge, is to form an interrupted circuit, of which the parts, where the interruption occurs, terminate by metallic balls, placed at a certain distance from each other. By varying the interval between them, we may regulate the quantity of electricity which we shall allow to accumulate in the battery; for the moment it exceeds the quantity of which that interval is the *striking distance* (§ 87,) an explosion happens, by the electricity forcing its way through the air from one ball to the other. If the balls be brought very near each other, a discharge will take place with a comparatively small accumulation: when farther separated, a greater charge will be retained, because a higher intensity of electricity is required in order to pass through the larger intervening space. It is on this principle that the instrument, called *Lane's Discharging Electrometer*, is constructed. It consists of a brass ball, B, *fig.* 35, placed at the end

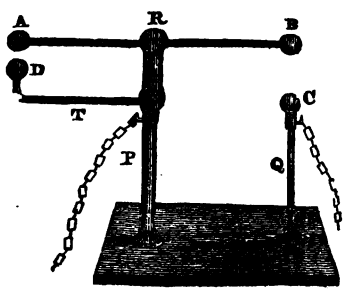
Fig. 35.

of a short metallic rod R, which moves through a tubular piece, supported by a bent glass stand S. This stand is made so as to be capable of being fixed, by its other extremity, to the rod passing up from the interior coating, and adjusted so that the ball B is immediately opposite to the knob of the jar, and may be brought to the exact *striking distance* from it which may be required: the other end of the moveable rod must be connected, by means of a chain or wire, with the outer coating.

The chief use of this instrument is to allow a jar to discharge itself spontaneously through any previously arranged circuit, without employing a discharging rod, or moving any part of the apparatus; and also to produce successive explosions nearly of the same strength. The magnitude of the charge is measured by the distance at which the balls are placed; and the power of the machine may be estimated by the number of explosions, which, at any given distance, take place in equal times. In Mr. Lane's experiment the shocks were twice as frequent when the interval between the balls was 1-24th of an inch, as when twice as much: hence he concluded that the quantity of electricity required for a discharge is in exact proportion to the distance between the surfaces of the balls. But the indications of this instrument are in reality subject to great fallacy, on account of the variable state of the atmosphere, which affects its conducting power; the quantity of dust which, even during the course of an experiment, is liable to be attracted, and to collect upon the balls; and also from the roughening and tarnishing of the metallic surfaces produced by frequent electric explosions. This last imperfection is one to which brass balls are particularly exposed; and might, if it were worth while, be remedied by having the balls made of fine silver.

(139.) Another contrivance for regulating the amount of the charge which we may wish to send through any substance, is that invented by Cuthbertson, and termed the *Balance Electrometer*. It consists of a metallic rod, R, *fig.* 36, terminated by two equal balls A, B, and balanced, like a scale-

Fig. 36.



beam, upon knife-edged centres. One of the arms of this beam is graduated, and carries a slider, which, when set at different distances from the centre of motion, acts on the lever with a proportionate weight from one grain to sixty. The ball A, at the extremity of this loaded arm, rests on a similar ball D, below it, which is supported by a bent metallic tube T, proceeding from the same stand as that which supports the rods; the whole being insulated by a glass pillar P. At a little distance below the ball B, at the other extremity of the beam, another ball C, insulated by the glass pillar Q, is placed; this last ball is to be connected by a chain with the outer coatings of the battery, while the metallic support of the balance is connected with the inner coatings. When a charge is communicated to the battery, the two balls A and D, which are in contact, become repulsive of each other; and when the force of this repulsion is sufficient to raise the weight on the loaded arm of the beam, the other arm will be forced down, and the ball B coming in contact with the ball C, the circuit will be completed and a discharge take place. As the force of the repulsion depends upon the intensity of the charge, the weight it has to overcome affords a measure of this intensity, and enables us to regulate its amount.

The practical application of accumulated electricity to various purposes of experiment, involves considerations which relate to the laws observed by electricity in its movements, and which more properly belong to the subject of the ensuing chapter.

Chapter X.

Of the Motion of accumulated Electricity.

(140.) In forming arrangements for directing the passage of accumulated electricity, it should be borne in mind that the electric fluid will, on these occasions, always pass through the best conductors, although they may be more circuitous, in preference to those which are more direct, but have inferior conducting power: and it must also be recollected, that when different paths are open for its passage, along conductors of equal power, the electricity will always take that which is the shortest. Thus if a person, holding a wire between his hands, discharges a jar by means of it, the whole of the fluid will pass though the wire, without affecting him: but if a piece of dry wood be substituted for the wire, he will feel a shock; for the wood, being a worse conductor than his own body, the charge will pass through the latter, as being the easiest, although the longest circuit. During its transit through the human body, in like manner, the shock is felt only in the parts situated in the direct line of communication; and if the charge be made to pass through a number of persons who take one another by the hand, and form part of the circuit between the inner and outer coatings of the jar, each will feel the electric shock in the same manner and at the same instant; the sensation reaching from hand to hand, directly across the breast. By varying the points of contact, however, the shock may be made to pass in other directions, and may either be confined to a small part of a limb, or be made to traverse the whole length of the body from head to foot.

(141.) By accurate experiments it appears that the force of the electric shock is weakened, that is, its effects are diminished, by employing a conductor of great length for making the discharge. But it is difficult to assign a limit to the number of persons through which even a small charge of electricity may be sent, so that all shall experience the shock; or to the distance along which it may be conveyed by good conductors. At an early period of electrical inquiries, much interest was attached to the determination of these points. The Abbé Nollet passed an electrical shock from a small phial through a hundred and eighty of the French guards in the presence of the king; and at the Carthusian convent in Paris, the monks were formed into a line of above a mile in length, by means of iron wires held between them: on the discharge of the phial, the sensation was felt at the same moment by all the persons composing this extensive circuit. Many experiments were made both by the English and French electricians with a view to ascertain the space which a discharge can be made to traverse, and the velocity with which it is transmitted. Of these the most ingenious and satisfactory were the experiments planned and executed by Dr. Watson, with the assistance of the leading members of the Royal Society. A circuit was formed by a wire which ex-

tended the whole length of Westminster bridge, at a considerable height above the river: one end of this wire communicated with the outer coating of a charged phial, the other being held by a person on the opposite side of the river, who formed a communication with the water by dipping into it an iron rod held by the other hand. The circuit was completed by another person, who stood near the phial, and who likewise dipped an iron rod into the river with one hand, and was enabled, by means of a wire held in the other, to effect a contact with the knob of the phial. Whenever the discharges took place, the shocks were felt by both persons; thus proving that the electric fluid must have been in motion along the whole line of the circuit, including both the wire above and the river below.

In another experiment, made on Shooters'-hill, at a time when the ground was remarkably dry, the electricity was made to perform a circuit of four miles; being conducted for two miles along wires supported upon baked sticks, and for the remaining distance, also of two miles, through the dry ground. As far as could be ascertained, by the most careful observation, the time in which the discharge was transmitted along that immense circuit was perfectly instantaneous: nor has any other trial that has yet been made afforded the least approach to a measurement of the velocity with which electricity moves.

(142.) On this subject, however, an important distinction should be made between the actual movement of each individual particle of electric fluid, and the transmission of an impulse along a series of such particles, for the one may bear hardly any proportion to the other: just as we find that sound proceeds with a velocity incomparably greater than that of the particles of air which are concerned in its propagation. In like manner the portion of blood, which raises the artery at the wrist, where the pulse is felt, is not the identical portion of blood which is thrown out from the heart by the contraction of that organ producing that pulsation: the impulse, in all these cases, being propagated like a wave, from one particle to another. There is, therefore, no reason to suppose that the same particles of electric fluid, which enter at one part, have traversed from one end to the other the whole line of conducting substances which form the circuit.

(143.) If we conceive the conducting bodies which compose the circuit to be divided into an indefinite number of filaments, every one of which is capable, in an equal degree, of conveying the electric fluid, it is evident that the united power of these filaments, or what is the same thing, the capability of the body itself to convey a charge of electricity, is in proportion to the number of these elementary filaments which it contains, that is, to the magnitude of its transverse section, without any relation to its form. Thus, the same metallic rod will conduct a charge equally well, whether it be flattened, or divided into several smaller wires, or whether it consist of a single cylinder of the same area.

(144.) If the size of the conductor be sufficiently great, the whole charge may be conveyed without any sensible obstruction or retardation, and therefore without any tendency to deviate from the direct line of its course. But it is otherwise when the conductor is too slender to afford a ready passage to the fluid which is pressing onwards: and it is important to inquire into the consequences to which these obstructions may give rise.

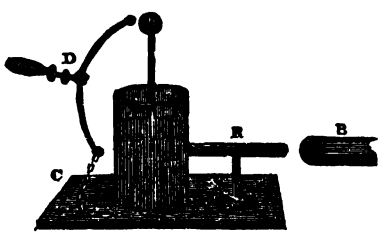
(145.) The first effect of an impediment to the free passage of accumulated electricity must be a retardation of its motion. It is reasonable, therefore, to expect that with a circuit composed either of bad conductors, or of conductors of inadequate size, although good, the discharge will not be effected so instantaneously, nor so completely; and that the shock which accompanies it will be diminished in its violence. This principle may find its application on occasions where it is desirable to soften the intensity of the shock, as in the medical employment of electricity, where imperfect conductors are on this account sometimes preferable, both for taking sparks and shocks.

(146.) A second effect resulting from an obstruction to the flow of electricity, is a tendency in the fluid to diverge from the direct line of its course, and to fly off to different objects in the vicinity. This is frequently exemplified in the case of lightning, which, on striking a building, is apt to take a very irregular and seemingly capricious route, darting towards conducting bodies which may happen to attract it, although at some distance from the immediate direction it was pursuing. The position of such

conducting bodies would appear to have a material influence in determining the striking distance. It was remarked by Dr. Priestley, that the explosion from a large battery extends to a greater distance over the surface of water than in air alone.

(147.) An effect which seems to depend upon this tendency in the fluid to divergence in consequence of obstruction, although it has by some been referred to a different principle, is that which has been termed *the lateral explosion*. When a large jar or battery is discharged by a metallic wire which is held in the hand without the protection of any glass or other insulating handle, it often happens that a slight shock is felt in the hand that grasps the wire, especially if the charge of electricity be very considerable. This apparent divergence or overflow of electric fluid, when rushing in large quantities through a narrow space barely sufficient to contain it, may also be rendered visible in other ways. If one end of a chain be connected with the outer coating of a charged jar, while the remainder of the chain is lying loosely upon a table, on discharging the jar in a darkened room, by a discharging rod, in the usual way, it will be found that the chain, although it makes no part of the circuit, is rendered luminous by the passage of sparks from one link to another. The following experiment, made by Dr. Priestley, may also be regarded as a case of lateral explosion. Let a thick metallic rod R, *fig.* 37, be supported on an insulating stand, and placed with one of its ends in contact with the outer coating of a Leyden jar; and at a distance of half an inch from its other extremity place a long conducting body B, of at least six or seven feet in length, and only a few inches in breadth. Let a chain C, be now placed upon the table, so that one of its ends may be about an inch and a half distant from the outer coating of the jar, and apply one end of the discharging rod D, to the other extremity of the chain. As soon as the other ball of the discharging rod is made to touch the knob of the jar, so as to effect a discharge, a brilliant spark is seen to extend between the insulated rod R, and the adjacent conductor B. This lateral spark has the same length and brilliancy whether it be received on flat or smooth surfaces, or on sharp points.

Fig. 37.



It is stated by Dr. Priestley, that the effect we have been describing takes place without any apparent change in the electrical state of the conductor B; and hence Cavallo conceived that the lateral spark was sent out from the jar, and returned to it almost at the same instant, allowing of no perceptible time for an electrometer to be affected. Dr. Robison, however, always observed, on repeating the experiment, that a very delicate electrometer was affected under these circumstances: and the same observation is confirmed by Biot.

The phenomena of the lateral explosion have been attempted to be explained by the electricity exerting, during its passage, an inductive influence, of which the effects may be expected to cease the moment the cause is removed. But this explanation appears to be less satisfactory than the one which attributes the phenomena to an expansive propulsion, followed by an immediate recession of electric fluid, produced by obstructions to its free passage in the circuit of conductors.

Chapter XI.

Effects of Electricity upon Bodies.

(148.) Having considered the circumstances attending the motion of electricity with reference chiefly to the fluid itself, we next proceed to give an account of the effects which it produces upon bodies by its passage through them.

(149.) Independently of electrical attraction and repulsion, it does not appear that the simple accumulation of electricity in any quantity in bodies, as long as it remains quiescent, produces the least sensible change in their properties. A person standing upon an insulating stool may be charged with any quantity of electricity from a machine, without being perceptibly affected, until the equilibrium of the fluid is disturbed, by drawing sparks from his body, or from the prime

conductor with which he may be in communication.

We have already seen, indeed, (§ 78, 79, 80,) that it is only a very small part of an electrified body, namely, the mere surface, that is in an active state, either of positive or negative electricity, and that the rest of the substance of the body is in a state of perfect neutrality.

(150.) It also appears that the uninterrupted passage of any quantity of electricity through a perfect conductor, such as a rod of metal which is of sufficient thickness to convey it, occasions no perceptible alteration in the mechanical properties of the conducting body.

(151.) On the contrary, very considerable effects are produced when a powerful charge is sent through a wire, which from the smallness of its size will not admit of the whole quantity to pass with perfect freedom; or through a substance which, although large, is deficient in conducting power; or, in other words, which opposes a degree of resistance to the passage of electricity. Thus, an iron conductor will carry off the whole electricity of a thunder-cloud in safety and in silence, while a beam of wood, or a tree, struck by lightning, is shivered into a thousand fragments.

(152.) When electricity thus changes the physical properties of bodies, its operation may, in general, be referred to that of separating their particles in the line of its course. This separation is effected with more or less violence, according to the intensityand quantityof the charge, and is frequently attended by the evolution of heat and light. The mechanical effects of electricity resemble those which would be produced by a material agent driven with great velocity and force through the substance of the body. Some of these effects, on the other hand, seem to be the consequences of the expansion produced by heat; but many of the changes induced by electricity are of a chemical nature, and such as mechanical agencies alone are insufficient to explain. We proceed to describe these several effects more particularly.

§ 1. *Mechanical Effects of Electricity.*

(153.) The cohesion of the particles of solid bodies may be conceived to oppose some resistance to the tendency of electricity to separate these particles from one another; for we find that fluids are more violently acted upon than solids, by the passage of the electric discharge. If the stem of a capillary tube, such as is employed for making thermometers, be filled with mercury, and placed so that the filament of this metal forms part of the circuit; on the discharge being made, the glass tube will be burst, and its fragments, together with the mercury, will be completely dispersed. If a fluid of inferior conducting power, such as water, be contained in a tube of larger diameter than in the preceding experiment, the passage, even of a moderate charge, will be sufficient to break the tube, and scatter its contents. Oil, alcohol, and ether, oppose still greater resistance than water to the passage of electricity, and they are expanded and scattered with still greater violence by a discharge being made to pass through them.

(154.) Beccaria introduced two wires through holes in the opposite sides of a perforated ball of solid glass of two inches diameter, the ends of the wires being separated by a drop of water, which occupied the centre of the perforation. On passing a shock through the wires and intervening drop, the ball was shattered with great violence. By a similar arrangement, Mr. Morgan succeeded in breaking green glass bottles filled with water, when the distance of the wires between which the explosion passed exceeded two inches. In this way, also, glass tubes, half an inch thick, with a bore of the same diameter, were burst with a very moderate charge, in Mr. Singer's experiments. If a cup-like cavity be turned in a piece of ivory, capable of receiving the half of a light wooden ball, with a small conical cell at the bottom of the cavity, and two wires be inserted into it through the sides of the ivory; on putting a drop of water, alcohol, or ether between the wires, and placing the ball over them in its cavity, and sending a charge through the drop of fluid, part of it will be suddenly converted into vapour, and the ball will be propelled with great violence. Even a common drinking glass, filled with water, may be broken by the explosive force with which vapour is formed at the point where the electricity passes. Beccaria constructed a small mortar with a ball, behind which a drop of water was placed, so as to be between the two wires that passed through the sides of the mortar. The charge being sent through the two wires, the drop of water was expanded with such force, as to drive out the ball with great velocity. Mr. Lullin, of Geneva, found that, by

using oil instead of water in this experiment, the ball was projected with still greater force.

(155.) If two wires be introduced into a soft piece of tobacco-pipe clay, so that their ends be near each other, and a shock passed through them, the clay will be curiously expanded in the interval between the wires. The experiment will not succeed if the clay be either too dry or too moist. If the clay be too dry, or the shock too powerful, the mass will be shivered into innumerable fragments. If the clay be placed in the tube of a tobacco-pipe, or in a glass tube, the expansion of the clay will be so considerable as to shatter the tube which contains it.

(156.) The expansion of air by the passage of the electrical fluid, either in the form of sparks or shocks, is shown in the following experiment of Kinnersley, the apparatus for which has been called the *Electrical Air Thermometer*. It consists of a glass tube closed at both ends by air-tight brass caps, through which two wires slide in the direction of the axis of the tube. These wires are terminated by brass balls, which are made to approach within the striking distance. To an aperture in the bottom of the lower cap is fitted a bent tube of glass which turns upwards, and is open at both ends; the bent part is filled with mercury, or with a coloured fluid, which may indicate by its rising or falling in the tube any dilatation or contraction that may take place in the air within the vessel. It is found that every time a spark passes between the brass balls, the fluid suddenly rises, but descends again to its former level immediately after each explosion; thus showing that the dilatation of the air, produced by the abrupt passage of electricity, is but of momentary duration.

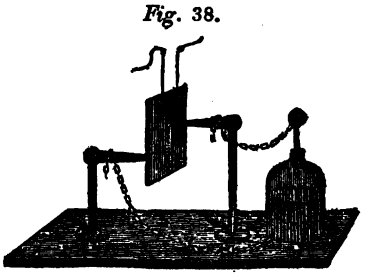
(157.) When a strong electrical charge is sent through a very confined portion of air, the explosive effects produced by it are as considerable as those we have seen exhibited by denser fluids. Thus if a piece of plate glass of the size of a square inch, and half an inch in thickness, be laid flat upon the small table of Henley's universal discharger, (§ 136,) and pressed down by a weight, and the points of the sliding wires be set opposite to each other and against the under edge of the glass, so that the electricity may pass beneath it, the charge of a large jar transmitted in this way will break the glass into innumerable fragments, and even reduce a portion into an impalpable powder. If the mouth of a small mortar made of ivory, with a cavity of half an inch diameter and an inch deep, be stopped by a cork, fitted so as to close the aperture accurately, yet without much friction, and if two wires be inserted through the sides of the mortar so that their points within the cavity be separated by an interval of about a quarter of an inch, a strong charge being sent through the wires will expand the air within the cavity so suddenly as to project the cork to some distance.

(158.) Solid bodies of a porous texture, such as wood, are easily torn asunder by an electric charge. If two holes be drilled in the opposite ends of a piece of wood, about half an inch long, and a quarter of an inch thick, and the ends of two wires inserted in the holes, so that their points may be at the distance of a quarter of an inch; on passing a strong charge through them, the wood will be split in pieces. Stones, loaf-sugar, and other brittle and imperfectly conducting substances, may be broken in a similar way.

Place a piece of dry writing paper upon the table of the universal discharger, and having removed the balls from the ends of the sliding wires, press the points of the wires against the paper at the distance of two inches from each other; if a powerful shock be now sent through the wires, the paper will be torn in pieces. If a number of wafers be placed on the table, instead of paper, they will be dispersed in a curious manner, and many of them broken into small fragments.

(159.) A singular result is obtained by the following variation in the circumstances of the last experiment, which was made by Mr. Lullin. Suspend a varnished card by silk threads, (see *fig.* 38,) in such a manner that two blunt

Fig. 38.



wires proceeding from the two sides of a jar or battery, may be in contact with

the opposite sides of the card, but at the same time half an inch distant from each other; when the discharge is made between the wires, and along the surface of the card, the latter is found to be perforated, but always at the point where the wire communicating with the negative side of the battery had touched it. The same perforation takes place at this point, even when a hole has been previously made at the point, where it is touched by the positive wire.

The course of the electric fluid may be traced with more precision, by having both sides of the card coloured, previously to the experiment, with vermilion, for it will then leave on the card a well defined black line extending from the point of the positive wire to the perforation; and a diffused black mark on the opposite side of the card, around the perforation, and next to the negative wire.

(160.) When the electrical discharge is made to pass in a perpendicular direction through the thickness of a card, which may be effected by placing it against the outer coating of a Leyden jar, and setting the lower ball of the discharging rod against the other side of the card, so that its thickness may be interposed between it and the tin-foil, and making the explosion in the usual way, as represented in *fig.* 33, (§ 134,) the card will be perforated. At the edge of the perforation, on each side of the card, there will be a small bur or protrusion, which is always larger on the side next to the jar, than on that next to the discharging rod; the former being the negative, and the latter the positive side. By passing the shock through a quire of paper, instead of a single card, the progress of this effect at different depths from the surface may be accurately analysed. Mr. Symmer, who devised this experiment, observed that the ragged edges were for the most part directed outwards from the body of the quire. Upon examining the leaves separately, however, he found that the edges of the holes were bent regularly two different ways, and more remarkably so about the middle of the quire; one edge of each hole being throughout its course forced one way, and the other edge in the contrary direction, as if the hole had been made in the paper by drawing two threads through it in opposite directions.

(161.) The following variation of the experiment illustrates the nature of the mechanical impressions made by electricity. Let a sheet of tin-foil be placed in the middle of a quire of paper; on making the discharge through it, the tin-foil is found to have received two indentations in opposite directions, and the leaves of paper are rent in such a manner, that on both sides of the tin-foil the burs point towards the outsides of the quire; but the indentations upon the tin-foil, and the burs on the paper, are in opposite directions. If another quire of paper be taken, and two sheets of tin-foil be placed within it, so that they are separated by the two middle leaves of the quire, the result will be that all the leaves will be perforated, excepting the two within the tin-foil, and in these two leaves there will be two impressions or indentations in opposite directions.

(162.) The mechanical effects we have just described have been often adduced, not only as proofs of the materiality of the electric fluid, but also as positive indications of the direction of its motions, according as either the one or the other of the two theories of electricity is adopted. But this is a subject which we reserve for future discussion.

(163.) The fracture of glass by the electrical explosion has already been adverted to, (§ 129;) but there are still a few circumstances attending it which deserve to be noticed. The edges of the fractured portion appear well defined on the positive side; while on the negative side they are splintered, as might be expected from the passage of a material agent from the former to the latter. It is remarkable also, that a perforation may be made in glass by a very moderate discharge, when the glass is in contact with oil or sealing-wax. Thus if a small phial, or glass tube, closed at one end, be filled with olive oil, and a pointed wire, bent at right angles, and passing through a cork fitted to the mouth of the phial or tube, be introduced into it, so that the point may touch any part of its inside beneath the surface of the oil; on suspending the vessel by its wire to the prime conductor of an electrical machine, and applying to the outside, either the knuckle, or a brass ball, exactly opposite to the point of the wire within, so that a spark may pass between them, it will be found to have made a small perforation through the glass; by bringing the wire in contact with different parts of the glass, a great number of holes may thus be made in it. The effect of the oil appears

to be that of controlling the tendency of the electric fluid to diverge, and of concentrating the whole power of the charge into a single point.

(164.) This repulsive tendency is also well illustrated by the following experiments made by Dr. Priestley. If a clean brass chain, previously dipped in melted resin, be laid upon paper, and the charge of a battery of at least 32 square feet be sent through it, the resinous coating will be thrown off from every part of the chain, which will be left perfectly clean, and free from resin. If a brass chain be laid upon a piece of glass, and a similar charge passed through it, the glass will be marked in a beautiful manner on every part of its surface, where it had been touched with the chain, every spot having the width and colour of the link. The metal may be scraped off the glass at the outside of the marks, but in the middle part it is forced within the pores of the glass. Dr. Priestley communicated a similar tinge to glass, by means of a silver chain, and small pieces of other metals; but he could not succeed with large pieces.

(165.) The effects of accumulated electricity upon metallic bodies, are referable, for the most part, to the agency of the heat produced by its passage through them; yet the phenomena, in many cases, indicate also the operation of other forces. By the transmission, through a piece of metal, of repeated shocks, which are not powerful enough to effect its fusion, or even ignition, a permanent alteration may be produced in its form, such as would not have resulted from heat alone. Dr. Priestley and Mr. Nairne found by experiment, that a chain through which an electrical charge had passed, undergoes a diminution in its length. A piece of hard drawn iron wire, ten inches long and one hundredth of an inch in diameter, was found, after fifteen discharges, to have lost one inch and one tenth of its length; and the increase of thickness seemed to be in proportion to this longitudinal contraction, for the wire had not perceptibly lost any of its weight during the experiment. A copper wire plated with silver, of the same dimensions as the former, underwent, by the same treatment, a diminution of length two thirds as great as that of the iron wire.

On the other hand, if the shocks be transmitted through a wire which has a weight suspended by it, so as to give it considerable tension, the length of the wire becomes increased instead of diminished, as in the above experiment. This is evidently owing to the influence of the heat which accompanies the passage of the electricity, and which diminishes the cohesion of the particles of the metal, and disposes them to yield to the extending force which the weight supplies.

§ 2. *Evolution of Heat by Electricity.*

(166.) The ignition and fusion of metals by the electric discharge, are phenomena which have been long observed. Thus by passing a strong charge through slender iron wires, they are ignited, and partly melted into globules. It was formerly believed that very large batteries were necessary for obtaining this effect; but if the wire be sufficiently fine, the electricity accumulated in a single jar of moderate size will suffice for its production. The best material for exhibiting this effect, is the finest flatted steel sold at the watchmakers' tool shops, under the name of watch pendulum wire. Van Marum has given a statement of the lengths of wires of different diameters, and of different metals, which his powerful machine enabled him to melt; when they were drawn to the thirty-second part of an inch in diameter, he found that he could fuse 120 inches of lead wire, and the same quantity of tin wire; five inches of iron wire; three inches and a half of gold wire; and only one quarter of an inch of wires of silver, copper, or brass.

(167.) From the experiments of Brooke and of Cuthbertson, it has been inferred that the length of wire which is thus melted by the electric discharge, varies as the square of the quantity of accumulated electricity which is sent through it; thus a combination of two jars, charged to an equal degree, will melt four times the length of wire which one jar will melt.

(168.) While the electric battery thus effects the fusion, and even in some cases the volatilization of metals, the phenomena appear also to indicate the action of propelling or dispersive forces, as if the agent concerned in their production was endowed with great mechanical momentum. Thus the densest metals are rent and dispersed with violence by the passage of accumulated electricity If a slip of gold or silver leaf be placed on white paper, and a

strong shock passed through it, the metal will disappear with a bright flash, and the impulse with which its particles are driven against the paper will produce a permanent stain of a purple or grey colour. Franklin found that if the metallic leaf be placed between two panes of glass firmly tied together, the explosion, provided the glass withstands the concussion, will leave on each of its surfaces an indelible stain, in consequence of some of the metallic particles being actually forced into the substance of the glass, and being then inaccessible to the action of chemical solvents applied to the surface of the glass. Sometimes it is found that these metallic stains extend to a greater distance than the breadth of the piece of metal. It often happens, however, that the pieces of glass themselves are shattered to pieces by the discharge.

(169.) The colours produced by the electric explosion of metals have been applied to impress letters or ornamental devices on silk and on paper. For this purpose Mr. Singer directs that the outline of the required figure should be first traced on thick drawing paper, and afterwards cut out in the manner of stencil plates. The drawing paper is then placed on the silk or paper intended to be marked; a leaf of gold is laid upon it, and a card over that; the whole is then placed in a press or under a weight, and a charge from a battery sent through the gold leaf. The stain is confined by the interposition of the drawing paper to the limit of the design, and in this way a profile, a flower, or any other outline figure may be very neatly impressed.

(170.) The heat evolved by electricity, like most other of its effects, is in proportion to the resistances opposed to its passage. The less the conducting power of a metal, the greater is the portion of it which the same shock can ignite or destroy. A rod of wood of considerable thickness being made part of the circuit, has its temperature sensibly raised by a very few discharges. Most combustible bodies are capable of being inflamed by electricity, but more especially if it be made to strike against them in the form of a spark or shock obtained by an interrupted circuit, as by the interposition of a stratum of air. In this way may alcohol, ether, camphor, powdered resin, phosphorus, or gunpowder be set fire to. The inflammation of oil of turpentine will be promoted by strewing upon it fine particles of brass filings. If the spirit of wine be not highly rectified, it will generally be necessary previously to warm it, and the same precaution must be taken with other fluids, as oil and pitch; but it is not required with ether, which usually inflames very readily. But, on the other hand, it is to be remarked that the temperature of the body which communicates the spark appears to have no sensible influence on the heat produced by it. Thus the sparks taken from a piece of ice are as capable of inflaming bodies as those from a piece of red-hot iron. Nor is the heating power of electricity in the smallest degree diminished by its being conducted through any number of freezing mixtures which are rapidly absorbing heat from surrounding bodies.

(171.) Light, as well as heat, is emitted during the electric discharge at every point where the circuit is either interrupted, or is occupied by bodies of inferior conducting powers. A moderate charge will produce a bright spark when made to pass through water, and the spark is still more luminous in oil, alcohol, or ether, which are worse conductors than water: on the contrary, in fluids of greater conducting power there is greater difficulty of eliciting electric light. Thus a much higher charge is required to produce a spark in hot water than in cold; a still higher in saline solutions; and in concentrated acids, light can be obtained only when their volume is very small; so that it is necessary for that purpose, to draw a line of the acid upon a plate of glass with a camel's hair pencil. This is illustrated by the following experiment mentioned by Singer. Draw a line with a pen dipped in water on the surface of a slip of glass; place one extremity of the line in contact with the coating of a Leyden jar, and at six inches distance upon the line place one knob of the discharging rod; when the jar is fully charged, bring the other ball of the discharger to the knob of the jar, and the discharge will take place luminously over the six inches of water. Next, trace a line with a pen dipped in sulphuric acid on a slip of glass, as in the former experiment, and place one extremity of it in contact with the outside of the jar; the ball of the discharger may then be placed on the glass at twelve inches distance, and the electric fluid will pass as brilliantly over that interval as over the six inches of water. In either of these experiments, if the line of fluid be wider in any particular part, the

light of the discharge will appear less brilliant in passing that portion; this must arise from the greater division of the fluid when passing over an extended conductor than over one that is narrow.

§ 3. *Chemical Effects of Electricity.*

(172.) Electricity exerts a most extensive and important influence in effecting changes in the chemical composition of bodies; but as this influence is most conspicuously exerted in that particular mode of agency, which is known by the name of *Galvanism*, this subject will more properly be considered in the treatise on that branch of electrical science. For the present, we must content ourselves with adducing a few instances, illustrative of the chemical effects of electricity in the forms under which it has now been presented to our notice.

(173.) Some of the chemical changes consequent on powerful electrical explosions, appear to be merely the effects of the heat which is evolved in that process. The surfaces of metallic bodies through which accumulated electricity is made to pass are frequently oxidated; this is seen more especially in the case of wires that have been fused or volatilized by the electric discharge. It is known that metals intensely heated are disposed to combine with the oxygen of the atmosphere, and, consequently, to assume the state of oxides; it is simpler, therefore, to ascribe this effect in the present case to a cause which is known to be in operation at the same moment, than to any peculiar or determining agency of electricity. A multitude of experiments are on record in which the partial oxidation of metals has been effected by electric explosions. This subject was prosecuted with minute and laborious attention by Van Marum, by Cuthbertson, and more lately by Singer. It is remarked by this last experimentalist, that the oxides of metals produced in this way appear to consist of several distinct portions of different degrees of fineness; when a wire is exploded in a receiver, part of the oxide immediately falls to the bottom, but another portion remains suspended in the air for a considerable time, and is at length gradually deposited. It is probable that this circumstance may in part account for the different colours of oxides produced in close receivers and in the open air, for in the latter case a portion of the oxide is always lost.

(174.) Under other circumstances, electricity is found to exert a power the reverse of the former; for it decomposes metallic oxides, extricating their oxygen, and restoring them to the metallic state. This deoxidating power was known to several of the earlier electricians. Beccaria reduced the oxides of tin and of mercury to their metallic state by electricity. In order to effect this change, a quantity of the oxide may be introduced into a glass tube, and pointed conducting wires inserted through corks at the opposite ends of the tube, so that a portion of the oxide may lie between them. This apparatus is then to be placed on the table of the universal discharger, (§136,) and repeated shocks are to be sent through the oxide until its partial or total reduction is accomplished. Vermilion, which consists of sulphur and mercury, is very easily decomposed by this process, and by a very moderate charge.

(175.) When a succession of electric discharges from a powerful electric machine are sent through water, a decomposition of that fluid takes place, and it is resolved into its two elements of oxygen and hydrogen, which immediately assume the gaseous form. This fact was discovered in 1789, by Messrs. Dieman, Paetz, and Van Troostwyck, who had formed themselves into a society for experimental research in Holland; and it completed the chain of evidence by which the great discovery of the composition of water, made five years before by Cavendish, is established. The abovementioned Dutch chemists being occupied, in conjunction with Mr. Cuthbertson, in investigating the effects of electricity when passed through different bodies, were desirous of ascertaining its effect on pure water. They employed for this purpose an apparatus consisting of a glass tube, twelve inches long and one-eighth of an inch in diameter, through one end of which a gold wire was inserted, projecting about an inch and a half within the tube; that end was then hermetically sealed. Another wire was introduced at the other end of the tube, which was left open, and passed upwards, so that its extremity came to a distance of five-eighths of an inch from the end of the first wire. The tube was then filled with distilled water, which had been freed from air by an excellent air-pump, and inverted in a vessel containing mercury. A little common air was let into the top of the tube, in

order to prevent its being broken by the discharge. Electrical shocks were then passed between the two ends of the wires through the water in the tube by means of a Leyden jar, which had a square foot of coated surface. This jar was charged by a very powerful double plate machine, which caused it to discharge twenty-five times in fifteen revolutions. At each explosion bubbles of air were formed, and rose to the top of the tube. As soon as a sufficient quantity had collected to leave the upper end of the wire uncovered by the water, so that the shock had now to pass through a portion of the mixed gases, they were instantly kindled; a reunion of the elements took place; water was again formed, and the space they had occupied was immediately filled with fluid from below, so as to restore every thing precisely as at the outset of the experiment. It was ascertained by the most decisive chemical tests, that the gases thus obtained consisted of a mixture of oxygen and hydrogen gases.

(176.) It may appear somewhat paradoxical that the same agent should, in the course of the same experiment, produce at one time decomposition, and at another combination of the same elements. The simplest way of reconciling this apparent discordance, is to suppose that the combination of the gases is the effect of the heat evolved during its forcible transit through an aeriform fluid that opposes considerable resistance to its passage; while the decomposition of the liquid is the direct consequence of the agency of electricity when not interfered with by heat.

(177.) Until lately, it was thought necessary to employ powerful machines and large jars in order to effect the decomposition of water by electricity, and that mere sparks from a common machine were inadequate to accomplish this purpose. That there is in this respect, however, no essential distinction in the operation of these two forms of electricity has been satisfactorily shown by Dr. Wollaston. This distinguished philosopher, perceiving, with his accustomed sagacity and penetration, that the decomposition would depend on duly proportioning the strength of the charge to the quantity of water, and that the quantity exposed to its action at the surface of communication depends on the extent of that surface, inferred that by reducing the surface of communication the decomposition of water might be effected by smaller machines, and with less powerful excitation than had hitherto been applied to this object. Having procured a small wire of fine gold, and given to it as fine a point as possible, he inserted it into a capillary glass tube; and after heating the tube, so as to make it adhere to the point, and cover it in every part, he gradually ground it down, till, with a pocket lens, he could discern that the point of the gold was exposed. When sparks from a prime conductor of an electrical machine were made to pass through water by means of a point so guarded, a spark, extending to the distance of one-eighth of an inch, would decompose water when the point exposed did not exceed one 700th of an inch in diameter. With another point, estimated at one 1500th, a succession of sparks one-twentieth of an inch in length afforded a current of small bubbles of air. With a still finer filament of gold, the mere current of electricity, without any perceptible sparks, evolved gas from water.

(178.) When a solution of sulphate of copper was subjected to the action of electricity by means of these slender conducting wires, the metal was revived around the negative wire; but upon reversing the direction of the current of electricity, so that the same wire now became positively electrified, the copper which had collected around it was redissolved, and a similar precipitate was deposited on the opposite wire, which was now the negative one. Similar experiments made with other metallic solutions were attended with analogous results; the negative wire always separating oxygen from its combinations, the positive wire always attracting it, and effecting its union with the bases presented to it. With solutions of neutral salts, the alkaline or earthy bases were attracted by the negative, while the acids were attracted by the positive wire. The experiments of Sir Humphry Davy have confirmed these results as far as concerns the chemical action of common electricity; but as this is a subject which bears more immediate relation to chemistry and to galvanism, it would not be right to enlarge upon it in the present treatise.

(179.) The magnetic effects of electricity will likewise form the subject of a distinct treatise, as they now constitute a new branch of science, under the title of ELECTRO-MAGNETISM.

§ 4. *Effects of Electricity upon Animals.*

(180.) Having seen that the effects of electricity on inanimate matter are of various kinds, we should be led to expect that its operation on living bodies would be still more complicated; for in addition to its mechanical and chemical agencies, it can hardly fail of exerting considerable influence on the living powers, and more especially on the functions of the nervous system. It is unnecessary to describe the sensations excited in the body by receiving electric sparks or shocks, since most persons in the present day are familiar with them. It is curious, however, to take a retrospective view of the mode in which the effects of the Leyden phial were announced to the world, on their first discovery. The philosophers who first experienced, in their own person, the shock attendant on the transmission of an electric discharge, were so impressed with wonder and with terror by this novel sensation, that they wrote the most ridiculous and exaggerated account of their feelings on the occasion. Muschenbroek states, that he received so dreadful a concussion in his arms, shoulder, and heart, that he lost his breath, and that it was two days before he could recover from its effects; he declared also, that he should not be induced to take another shock for the whole kingdom of France. Mr. Allemand reports, that the shock deprived him of breath for some minutes, and afterwards produced so acute a pain along his right arm, that he was apprehensive it might be attended with serious consequences. Mr. Winkler informs us, that it threw his whole body into convulsions, and excited such a ferment in his blood, as would have thrown him into a fever, but for the timely employment of febrifuge remedies. He states, that at another time it produced copious bleeding at the nose; the same effect was produced also upon his lady, who was almost rendered incapable of walking. These strange accounts naturally excited the attention and wonder of all classes of people; the learned and the vulgar were equally desirous of experiencing so singular a sensation, and great numbers of half-taught electricians wandered through every part of Europe to gratify this universal curiosity.

(181.) As it is probable that the electric fluid meets with greater impediment in passing from the surface of one bone to another, at the parts where the continuity of substance is interrupted by the joints, this circumstance explains why the shock is often more especially felt at the joints than in any other part of a limb. But if the shock be directed more particularly through muscles, its effects are chiefly shown by exciting a convulsive and involuntary action of those muscles. This is often observed to take place in a paralysed limb, when electric shocks are sent through it, although the nerves of the limb are at the time incapable of conveying the impressions which produce sensation. Mr. Morgan states, that if the diaphragm be included in the circuit of a coated surface of two feet in extent, fully charged, the sudden contraction of the muscles of respiration will act so violently upon the air in the lungs, as to occasion a loud and involuntary shout; but if the charge be small, a fit of convulsive laughter is induced, presenting a most ludicrous exhibition to the by-standers.

(182.) It is on the nervous system, however, that the most considerable action of electricity is exerted. A strong charge passed through the head, gave to Mr. Singer the sensation of a violent but universal blow, and was followed by a transient loss of memory and in distinctness of vision. If a charge be sent through the head of a bird, its optic nerve is usually injured or destroyed, and permanent blindness induced: and a similar shock given to larger animals, produces a tremulous state of the muscles, with general prostration of strength. If a person who is standing receive a charge through the spine, he loses his power over the muscles to such a degree, that he either drops on his knees, or falls prostrate on the ground; if the charge be sufficiently powerful, it will produce immediate death, in consequence, probably, of the sudden exhaustion of the whole energy of the nervous system. Small animals, such as mice and sparrows, are instantly killed by a shock from thirty square inches of glass. Van Marum found that eels are irrecoverably deprived of life when a shock is sent through their whole body; but when only a part of the body is included in the circuit, the destruction of irritability is confined to that individual part, while the rest retains the power of motion Different persons are affected in very

different degrees by electricity, according to their peculiar constitutional susceptibility. Dr. Young remarks, that a very minute tremor, communicated to the most elastic parts of the body, in particular to the chest, produces an agitation of the nerves, which is not wholly unlike the effect of a weak electricity.

(183.) The bodies of animals killed by electricity, rapidly undergo putrefaction, and the action of electricity upon the flesh of animals is also found to accelerate this process in a remarkable degree. The same effect has been observed in the bodies of persons destroyed by lightning. It is also a well-established fact, that the blood does not coagulate after death from this cause.

(184.) It has not been determined with any degree of certainty, whether electricity, in its ordinary mode of application, exerts any sensible influence on the functions of the animal system. The Abbé Nollet persuaded himself, from the experiments he made on man and animals, that the perspiration was increased during the time they were electrified; and De Bozes had noticed that the pulse was quickened under the same circumstance. But Van Marum, on repeating these experiments in a variety of ways, met with such variable and contradictory results, that he could deduce from them no satisfactory conclusion respecting the real operation of electricity; and, indeed, if we take into account the powerful influence which the imagination exerts on most persons who are the subjects of such experiments, as well as on those who witness them, there appears but little chance, amidst such multiplied sources of fallacy, of arriving at the truth. The only general fact, perhaps, which appears to be established, is that electricity acts as a stimulant both to the muscular and the nervous systems.

(185.) When the energetic effects of the shock from the Leyden phial were first made known, the most sanguine expectations were immediately raised, that electricity would prove an agent of considerable power in the cure of diseases. It was supposed that as a stimulant, it would have many advantages over other remedies; for it can be administered in various degrees of intensity, which may be regulated with great exactness; and its application can be directed especially to the organ we wish to affect, and can be limited to that organ, so as not to interfere with the functions of the general system. Accordingly we find, that at one period electricity was in great repute as an efficacious remedy in a number of diseases; but at present it is seldom employed except in a very few. It is not unfrequently had recourse to in palsy, contractions of the limbs, rheumatism, St. Vitus's dance, and some kinds of deafness, and impaired vision; it has also been applied to discuss tumours, to remove obstructions, and to relieve pain.

(186.) Electricity may be administered medicinally in four different ways. The first and most gentle is under the form of a continued stream, or *aura* as it is termed, derived from a wire or pointed piece of wood connected with the prime conductor of the machine, held by an insulated handle, at the distance of one or two inches from that part to which it is to be directed; an impression is felt similar to a current of air; and in this way it may be borne by parts of great sensibility, such as the eye. The second mode is by directing sparks of various sizes to the affected part, by means of a metallic ball at the extremity of a brass rod, which is within a moderate distance from the part; or else by placing the patient on an insulating stool, and while he is in communication with the prime conductor of the machine, taking sparks from him by another person with a metallic ball at the end of a rod which he holds in his hand. The size and intensity of the spark will, of course, be regulated by the distance at which the ball is placed from the body, provided the machine be steadily worked. The third mode is that by shocks from the discharge of a Leyden phial, which is, of course, the most severe and painful method of applying electricity. Great caution is required against the indiscriminate application of this last method, which is not wholly free from danger. The fourth mode is by Galvanism, hereafter to be noticed.

§ 5. *Effects of Electricity upon Vegetables.*

(187.) It has also been imagined that electricity acts as a stimulus to vegetable life: and many fanciful projects of improvements in horticulture by the aid of artificial electricity have been entertained. It is needless, however, to enlarge upon these visionary speculations, the fallacy of which has been sufficiently shown by the late Dr. Ingenhouz, who

upon the most accurate inquiry, found that the vegetation of plants was in no sensible degree either promoted or retarded by common electricity. The experiments of Van Marum, however, in which be found that electricity increased the evaporation of plants, appear to be entitled to some confidence; but still the effect observed, may, as he himself remarks, have been occasioned by the increased current of air from the parts of the electrified leaves. His observations on the influence of electricity on the sensitive plant, (*Mimosa pudica,*) deserve also to be noticed. The mere approach of an electrified conductor, whether charged with positive or negative electricity, produced no effect upon the plant; but when sparks were taken from it, the leaves collapsed, just as they would have done by concussions of a mechanical nature, and in other respects the plant underwent no change. In the *Hedysarum gyrans*, a plant remarkable for the continual rotatory motions of its leaves, electricity appeared to have no sensible influence either in accelerating or retarding these movements.

(188.) The passage of shocks through living plants immediately destroys the vitality in the parts through which the shock has been sent. It is, indeed, very easy to kill plants by means of electricity. A very small shock, according to Cavallo, sent through the stem of a balsam, is sufficient to destroy it. A few minutes after the passage of the shock, the plant droops, the leaves and branches become flaccid, and its life ceases. A small Leyden phial, containing six or eight square inches of coated surface, is generally sufficient for this purpose, which may even be effected by means of strong sparks from the prime conductor of a large electrical machine. The charge by which these destructive effects are produced, is probably too inconsiderable to burst the vessels of the plant, or to occasion any material derangement of its organization; and, accordingly, it is not found, on minute examination of a plant thus killed by electricity, that either the internal vessels or any other parts have sustained perceptible injury.

(189.) It appears from the experiments of Mr. Achard, that the fermentation of vegetable matter is accelerated by electricity.

(190.) The general conclusion deducible from these inquiries is, that feeble electricity exerts no perceptible influence on either animal or vegetable life: but when transmitted in powerful shocks, its destructive effects are similar to those which are produced by lightning.

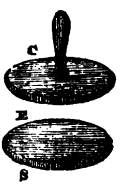
Chapter XII.

Instruments adapted to collect weak Electricity.

(191.) Before we proceed to consider the developement of electricity under various circumstances, it will be proper to give a description of several instruments which have been contrived for the purpose of collecting and exhibiting weak degrees of electricity, that would otherwise escape detection. All these instruments derive their efficacy from the principle of electric induction; and their mode of operation will be best understood by previously directing our attention to the electrophorus.

(192.) The instrument termed the *Electrophorus* was invented about the year 1774 by Professor Volta, a name which is associated with many important discoveries in the science of electricity. It consists of three parts: the essential part, which supplies the electricity, being a cake of some electric substance, (E, *fig.* 39,) such as sulphur,

Fig. 39.



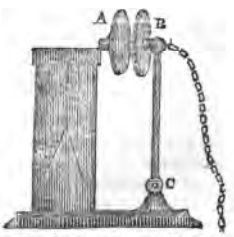
gum lac, sealing-wax, pitch, or other resinous composition; this is melted on a conducting plate S, called *the sole*, which is formed with a rim to contain it, and the fluid then allowed to congeal. The third part of the apparatus consists of a circular metallic plate C, provided with an insulating handle fixed upon its upper surface. This is called *the cover;* and is sometimes made of wood, covered on all sides with tin-foil well rounded at the edges to prevent the dispersion of electricity. In order to bring the apparatus into a state of activity, the surface of the cake is excited by friction with fur or flannel, and is thus rendered negatively electrical. The cover, held by its insulating handle, must now be placed

on the cake: in this situation it does not come sufficiently in contact with the cake to receive its electricity, but acquires by induction an opposite state at its lower surface, and a similar state at its upper; that is, the cake being negative, the under side of the cover will be positive, and the upper side negative. If, while in this state, the upper negative surface be touched with the finger, or with any other conductor communicating with the earth, a spark will pass from the latter to the cover, so as to restore the electric equilibrium; the quantity of electricity thus superadded being retained in the cover by the inductive influence of the cake. But when the plate is raised, provided it be held by its insulating handle, the action of the cake being withdrawn, the cover is found to be charged with positive electricity, which may be imparted to an insulated conductor, or to a Leyden jar. This operation may be repeated an indefinite number of times, since the electricity of the cake continues unimpaired during the process, and thus may a charge be communicated to the jar of an intensity equal to that of the cover of the electrophorus when raised. The instrument has been known, indeed, to retain its power undiminished for months, and may therefore be regarded as a sort of magazine of electricity. It is obvious, that if the cover were simply placed on the cake, and again raised without previously touching it, it would then exhibit no sign of electricity. If the sole of the electrophorus be insulated, a spark may be obtained from it, when the cake has been excited; and if while placed on the cake the cover be touched with the finger, and at the same time the sole be touched with the thumb, a sensible shock will be felt in that part of the hand.

(193.) Volta is also the inventor of an instrument acting on the same principle as the electrophorus, and which he termed *the condenser*, of which the purpose is to collect a weak electricity, spread over a large surface, into a body of small dimensions, in which its intensity will be proportionably increased, and therefore become capable of being examined. A small metallic plate, connected with the substance of which the electricity is to be determined, is brought within a very small distance of another plate communicating with the earth. The small portion of electricity received from the substance to be tried by the first plate, acts by induction on the second plate, and occasions it to acquire the opposite electrical state: this latter state reacts upon the first plate, increasing its capacity for the electricity which it had first received, and tends to accumulate a larger quantity in it, which quantity it must derive from the substance with which it communicates. This mutual action and reaction continues till an equilibrium is attained. If the communication between the substance tried and the first plate be broken off, and the plate thus insulated be removed from the contiguity of the second plate, the accumulated electricity with which it is charged will become evident upon its application to an ordinary electroscope, such as those described in § 13 and 14.

(194.) Various have been the forms given to the condenser, according to the fancy of electricians, without any change in the principle on which it acts. In general, the two plates are merely separated by a thin stratum of air. Sometimes their surfaces are covered with a non-conducting varnish, which prevents any communication of electricity from the one plate to the other, while it allows of a very near approach of the plates to each other; but this method is liable to objection, from the permanent electricity which the varnish sometimes contracts by friction, and which may interfere with the regular operation of the instrument. One of the most convenient forms is that of the condensing electrometer, (*fig.* 40,)

Fig. 40.



in which the first plate of the condenser A, is fixed to the cap of the gold-leaf electroscope; the second plate B, which communicates by a chain with the ground, being moveable round a joint C, and thus capable of being turned back and removed from the first plate, so as to allow its electricity to be manifested by the divergence of the gold leaves.

(195.) The instruments called *Doublers* are so contrived, that by executing certain movements, very small quantities of electricity communicated to a part of the apparatus may be continually doubled, until it becomes perceptible by an electroscope. The first invention of this kind was that of Mr. Bennet, which consists of three brass plates, which we shall call A, B, and C. The plate A has an insulating handle fixed in its centre, while the plate B has a similar handle fixed in its circumference. The under side of A, and both sides of B are covered with varnish. The third plate C is also of brass, and is only varnished on its upper side, the lower side communicating with the gold-leaf electroscope. The body whose electricity is to be tried, is made to communicate with the under side of the plate C, which touches the electroscope, while B is placed upon C, and then touched with the finger: the communication with the electrified body is then removed, and B is lifted up by its insulating handle. A is then placed, by means of its handle, upon B thus elevated. A is then touched, and, after withdrawing the finger, is separated from B. In this process B acquires an electricity contrary to that of C; and A an electricity contrary to that of B, that is, the same as that of C. If the plate A, thus electrified, be next applied to the under surface of C, and B be again applied over C, and touched with the finger as before, it will be acted upon by the electricities contained both in C and A, and thus acquire, by induction, nearly double the quantity which it had done in the first operation. The consequence of this will be that nearly all the free electricities of A and C will be concentrated in C. A may now be removed, and after withdrawing the finger from B, B may also be removed, and C will be left with double the quantity of electricity which it had received from the body with which it was originally made to communicate.

If after this duplication the electricity of the plate C be still too feeble to be indicated by the electroscope, the same series of operations must be repeated ten or even twenty times; when by doubling it every time, the smallest conceivable quantity of electricity must at last be rendered sensible; since, at the end of the twentieth operation, it will be augmented more than 500,000 times. Although the frequent repetition of the operations may appear tedious, yet, by a little practice, the art is readily acquired, and the whole process need not occupy a minute. Great care must be taken in conducting these experiments, not to excite any electricity by the friction of the finger, or by any other means, in the varnished sides of the plates. In order to obviate this source of error, Cavallo contrived a form of the instrument, that enabled the plates to be brought within a very small distance of one another, yet without actual contact, so as to enable him to dispense altogether with the employment of varnish. But notwithstanding every precaution of this kind, it is always found that the instrument exhibits electricity of itself, although none has been previously communicated to it: so that its indications cannot be at all depended upon for the detection of very minute quantities of electricity. It is unnecessary, therefore, to describe the particular mechanisms invented by Dr. Darwin, and improved by Nicholson, for bringing the plates into the requisite positions, and effecting in succession the necessary contacts, by the simple rotation of a winch, aided by wheelwork: instruments which have gone by the names of the *moveable*, or *revolving doubler*, and the *multiplier of electricity*, and which are now superseded in practice by instruments more sensible and certain in their operation.

Chapter XIII.

Developement of Electricity by Changes of Temperature and of Form.

(196.) There are certain mineral bodies, which, from being in a neutral state at ordinary temperatures, acquire electricity simply by being heated or cooled. This property is possessed only by regularly crystallized minerals; and of these the most remarkable is the tourmalin, which is a stone of considerable hardness, found in many parts of the world, and particularly in the island of Ceylon. The Dutch, who first became acquainted with it in that island, gave it the appellation of *Aschentrikker*, from its property of attracting ashes when it is thrown into the fire. It appears from the researches of Dr. Watson, that its attractive properties were known to Theophrastus, who describes it under the name of *Lyncurium*. Linnæus has termed it the *Lapis Electricus*, (Electric stone.) The form of its crystals is generally that of a nine-sided prism, terminated by a

three-sided pyramid at one end, and by a six-sided pyramid at the other. Lemery noticed its electric properties in the year 1717; but the first scientific examination of them was made by Æpinus in 1756, and published in the Memoirs of the Berlin Academy. He found that when a crystal of tourmalin has its temperature raised to between 100° and 212° of Fahrenheit, one extremity, which is that terminated by the six-sided pyramid, becomes charged with positive electricity, while the other extremity is negative; so as to be capable of affecting a delicate electroscope. When the stone is of considerable size, flashes of light may be seen along its surface. Mr. Wilson, who made many experiments on this subject, observed that a flat tourmalin retained its electricity without diminution, after exposure to intense heat for half an hour; but Canton, upon repeating these experiments, did not obtain the same result. Hauy states, that very high degrees of heat destroy the electricity of the tourmalin. After this has been effected, it recovers its electricity as it gradually cools: but in that case the electric states are generally reversed; that extremity, or *pole*, as it has been called, which was before positive, is now negative, and *vice versâ*. It is only at the summits of the pyramids, by which the crystal is terminated, that the electricity is manifested; the intermediate portions exhibiting no sign of electrical excitation, unless the stone be broken in pieces; and then each fragment is found to possess a positive and a negative pole, like the entire crystal. This fact bears a striking analogy to a corresponding property in magnets. At the ordinary temperature of the atmosphere, the tourmalin may be rendered electrical by friction.

(197.) There are several other gems and crystallized minerals which possess the same property as the tourmalin. The luminous appearance of some diamonds, when heated, is ascribed by Sir Humphry Davy to their electrical excitation. The substance called the *Boracite*, composed of borate of magnesia, which crystallizes in cubes, having its edges and angles defective, becomes electrical by heat, and in one variety presents no less than eight sides, alternately in different states; that is, four positive and four negative; the opposite poles being in the direction of the axes of the crystal. In those varieties in which only four of the angles of the crystal are truncated, that is, cut off by planes, while the rest are either entire, or are replaced by more than one plane, it is always the former of these angles that become positive, and the latter negative.

(198.) Similar properties are possessed by the Topaz, which consists of siliceous fluate of alumina; its electric poles are situated upon the two opposite summits of the secondary crystal. In some varieties, Hauy found a series of consecutive poles alternately positive and negative. Axinite, Mesotype, and Prehnite, become electrical by the application of heat: as also the two following metallic oxides, namely Calamine, which is an oxide of zinc, and Sphene, or calcareo-siliceous oxide of titanium. Mr. Dessaignes has lately shown that all metallic bodies are capable of a feeble electric excitation by changes of temperature. It results from the researches of Hauy, that this electrical property in mineral bodies is intimately related to the laws of their crystallization, and also to the direction in which the light is most readily transmitted through them.

(199.) There are a great many substances which become electrified on passing from the liquid to the solid form. This happens to sulphur, gum lac, bee's wax, and in general all resinous bodies. Unless proper precautions be taken, however, we frequently obtain no indications of this electricity, because it is usually *disguised*, that is, rendered inactive by the opposite electricity of the contiguous substances. Thus, if sulphur be melted over the fire in an iron ladle, and then set by to cool and harden, it exhibits no sign of electricity; because the negative electricity of the sulphur is exactly counterbalanced by the positive electricity accumulated in the iron vessel which contains it. But if the sulphur be removed from the vessel, which may be done by again heating it for a short time, so as just to melt the surface in contact with the iron, and allow of its being detached when the ladle is inverted, on suffering the sulphur to cool in this situation, its electricity becomes very apparent. If sulphur be melted in a wine glass, the conical shape of which admits of its being taken out when cold, the opposite electricities of the two surfaces will then manifest themselves, that of the sulphur being negative, and that of the glass positive; but when the sulphur is replaced in the glass, all indications of

electricity disappear. The electricity developed by the process of cooling was called by Wilke, who first observed it, *spontaneous electricity*, in contradistinction to that which, originating from friction, he called *excited electricity*. Van Marum, however, attributes the electricity developed by the separation of the two substances, to a species of friction; for he remarks, that the electricity does not manifest itself till the sulphur begins to contract in the act of congelation, and that it attains its maximum at the point of the greatest contraction.

(200.) It is reasonable to suppose that whatever change was produced in the electrical state by congelation, the reverse would be produced by liquefaction. We are not aware of any experiments which bear directly upon this question.

(201.) The conversion of bodies into the state of vapour, as well as the condensation of vapour, is generally attended by some alteration of their electrical condition; and the bodies in contact with the vapour are thereby rendered electrical. Thus, if a plate of metal strongly heated be placed upon a gold-leaf electroscope, and water be dropped upon the plate, at the moment the vapour rises the leaves of the electroscope diverge with negative electricity. The general fact was noticed by Laplace, Lavoisier, and Volta, in the year 1781; and was found to extend both to solids and to liquids passing into a gaseous form. De Saussure made an extensive series of experiments on the ebullition of water and other fluids, with a view to ascertain the degree and kind of electricity developed during this process. But investigations of this kind are attended with great difficulty, from the multitude of minute circumstances which are liable to affect the results; and we accordingly find, that different experiments of the same kind often afford the most opposite conclusions.

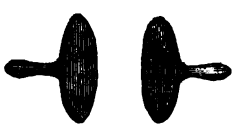
(202.) In general it is found, that the vaporization of water by simple ebullition produces negative electricity in the remaining fluid, or vessel which contains it: the vapour itself being positive. On the contrary, when aqueous vapour is condensed into water, it becomes negative, leaving the bodies with which it was last in contact in a state of positive electricity. Yet in some of De Saussures's experiments, when the heat was communicated to a quantity of water contained in an insulated metallic vessel, by throwing into it a mass of red-hot iron, the electricity was very strongly positive. This difference in the result was probably owing to the chemical decomposition of the water in the latter experiment, a circumstance which, as we shall presently see, is itself a source of electricity. It is principally on account of the interference of chemical actions with the regular operations of temperature, and of the complications introduced by electric induction, that experiments on this subject have hitherto presented such anomalous, and, apparently, discordant results.

Chapter XIV.

Developement of Electricity by Contact, Compression, and other mechanical Changes in Bodies, and also by their Chemical Action.

(203.) It had long been suspected, rather than proved, that a feeble degree of electricity is evolved by the contact or collision of different metals: but this important fact was established in the clearest manner by Volta, about the year 1801. The apparatus he employed in his investigations on this subject consisted of two discs, the one of zinc, the other of copper, (*fig.* 41,) rather more

Fig. 41.



than two inches in diameter, ground perfectly plane, and having in their centres insulating handles perpendicular to their surfaces, by means of which the plates could be brought into contact, without being actually touched with the hand. With this precaution the discs were made to approach till they touched one another; they were then separated, by keeping them parallel as they were drawn back. The electricity they possessed after this separation was then examined by means of the condenser; and, that the effects might be rendered more distinct, the electricity produced by a number of successive contacts, (taking care to restore the discs to the neutral state after each contact,) was accumulated in the same condenser. It was constantly found that the copper disc charged the condenser with negative, and the zinc disc with positive elec-

tricity. Thus it was established as a general fact, that these two metals, insulated, and in their natural state, are brought, by mutual contact, into opposite electrical states; the zinc acquiring positive electricity, and the copper becoming, in an equal degree, negative.

(204.) No explanation has yet been given of this curious fact, which seems to be at variance with all the previously ascertained laws of electric equilibrium. The transfer of electricity from one metal to the other during their contact, implies the operation of some new force which no theory has yet embraced. While the contact is preserved, neither of the metals gives any indication of its electrical state, the electricity being *disguised;* as would be the case of that of the coatings of a Leyden jar, if we could suppose them both in actual contact, but yet incapable of allowing any transfer of the electricity from the one to the other, so as to restore both to the state of neutrality.

We shall have occasion to resume the consideration of this curious subject in the treatise on Galvanism, with the theory of which it appears to have an intimate relation.

(205.) There are some bodies which are rendered electrical by pressure. This property is possessed in the most remarkable degree by that transparent variety of carbonate of lime which is known by the name of *Iceland spar.* According to Hauy, if a crystal of this spar, which has the form of a rhomboid, be held in one hand by two of its opposite edges, and if at the same time two of its parallel planes be lightly touched by two fingers of the other hand, and then brought near to the small needle of the electroscope, (§ 12) a decided attraction will be perceptible. By applying a more powerful pressure, the electrical effects will be still more considerable; the electricity being in all cases positive. Hauy observes that this property resides principally in those crystalline minerals that are capable of being reduced by mechanical division to plane and smooth laminæ: such as the Topaz, especially the colourless variety; Euclase, Arragonite, Fluate of lime, and Carbonate of lead. Among those substances in which friction excites negative electricity, there are some which require only to be pressed, for the production of the same effect. An instance occurs in elastic bitumen, when it has been cut into a proper shape for the experiment. Mr. Becquerel has lately discovered that many other substances, such as cork, bark, hairs, paper, and wood, possess the property of producing electricity by compression.

(206.) Many substances, when reduced to powder, exhibit electricity, if they are made to fall upon an insulated metallic plate. This fact was first noticed by Mr. Bennet, after he had invented his gold-leaf electroscope. He found that powdered chalk, put into a pair of bellows, and blown upon the cap of the electroscope, communicates to the instrument positive electricity, when the pipe of the bellows is about six inches from the cap; but the same stream of powdered chalk electrifies it negatively at the distance of three feet. On being blown in a more copious stream from a pair of bellows without the pipe, the electricity is always negative; and the same effect takes place when the powder is let fall from another plate upon the cap of the instrument. This subject was pursued by Cavallo; but the most complete set of experiments relating to it is that of Singer, who employed in his researches the two following methods: first, that of sifting the powders on the cap of a delicate electrometer through a fine sieve, which was thoroughly cleaned after each operation; and secondly, that of bringing an insulated copper plate repeatedly in contact with extensive surfaces of the powders spread on a dry sheet of paper; the copper plate being brought in contact with the condenser after every repetition of the contact, until a sufficient charge was communicated.

(207.) The following substances, according to Singer, produce negative electricity when sifted on the cap of the electrometer: *viz.* copper, iron, zinc, tin, bismuth, antimony, nickel, black lead, lime, magnesia, barytes, strontites, alumine, silex, brown oxide of copper, white oxide of arsenic, red oxide of lead, litharge, white lead, red oxide of iron, acetate of copper, sulphate of copper, sulphate of soda, phosphate of soda, carbonate of soda, carbonate of ammonia, carbonate of potash, carbonate of lime, muriate of ammonia, common pearl-ashes, boracic acid, tartaric acid, cream of tartar, oxymuriate of potash, pure potash, pure soda, resin sulphur sulphuret of lime, starch, orpiment.

(208.) The following substances produce positive electricity under the same circumstance: *viz.* wheat flour, oatmeal, lycopodium, quassia, powdered cardamom, charcoal, sulphate of potash,

nitrate of potash, acetate of lead, oxide of tin.

(209.) The following catalogue exhibits the results of the experiments of contact with a copper plate; the different substances being arranged under the head of the electricity they really acquire, which is contrary to that of the copper plate. *Positive:* lime, barytes, strontites, magnesia, pure soda, pure potash, common pearl-ashes, carbonate of potash, carbonate of soda, tartaric acid. *Negative:* benzoic acid, boracic acid, oxalic acid, citric acid, silex, alumina, carbonate of ammonia, sulphur, resin. These experiments were several times repeated with uniform results.

(210.) The above mode of electrical excitation is probably merely a species of friction, differing only from the more ordinary instances by the mode of its application. But in other cases the electrical effects of contact are more distinctly exhibited, as when zinc filings are poured through holes in a plate of copper, upon the cap of an electrometer.

(211.) The following experiment, founded on one devised by Professor Lichtenberg of Gottingen, is an elegant illustration of the opposite electrical states of different powders. With the knob of a charged jar, trace on the surface of a smooth plate of glass, or of any resinous substance, various lines at pleasure; and then repeat the same operation in other parts with the knob of a jar charged with the opposite electricity. Let the surface thus prepared be gently dusted, by means of a powder-puff, with a mixture of powdered sulphur and red lead, previously triturated together in a mortar. By the contact and friction thus produced, the sulphur has been rendered negative, and the red lead positive; and each of the powders, when projected on the plate, will attach itself to the oppositely electrified lines, forming a series of red and yellow outlines. It is also observable, that the configurations assumed by these and other powders differ according to the species of electricity impressed upon the plate; positive electricity producing an appearance resembling feathers, and negative electricity an arrangement more like stars.

(212.) The most important circumstance in this inquiry, is the connection between electricity and the chemical properties of matter. It is observed by Sir H. Davy, that most of the substances that act distinctly upon each other electrically, are likewise such as act chemically, when their particles have freedom of motion: this is the case with the different metals, with sulphur and the metals, with acid and alkaline substances. Of two metals in contact, the one which has the greatest chemical attraction for oxygen acquires positive electricity, and the other the negative: so that if arranged in the order of their oxidability, as follows, zinc, iron, tin, lead, copper, silver, gold, platina, each will become positive when brought into contact with any that follow it in the series, and negative with any of those which precede it. In contacts of acids with bases, as of crystals of oxalic acid with dry quicklime, the former is negative, the latter positive. All acid crystals when touched by a plate of metal render it positive, the crystals themselves becoming negative.

(213.) Bodies that exhibit electrical effects by mutual contact, previous to their chemical action on each other, lose this power during combination. Thus if a polished plate of zinc be made to touch a surface of dry mercury, and quickly separated, it is found positively electrical, and the effect is increased by heat; but if it be so heated as to amalgamate, that is, unite chemically with the mercury, it no longer exhibits any signs of electricity. The case is analogous with copper and sulphur; and iron, when applied to mercury, produces more electricity than zinc, apparently from its being incapable, under ordinary circumstances, of forming a chemical combination with mercury.

(214.) On the other hand, there can be no question that electricity is occasionally, if not universally, elicited during chemical action. We have just seen that a dry acid becomes negative by contact with a metal, which is consequently thereby rendered positive. In this case no chemical combination had taken place. But Becquerel has shown that if the acid, instead of being in a dry crystalline form, be in a liquid state, and capable of acting chemically on the metal, the acid will become positive and the metal negative. The same conclusion may also be deduced from the experiments of Lavoisier and Laplace, on the action of dilute sulphuric acid on iron filings. That the oxidation of metals gives rise to electricity has been also shown by the experiments of Dr. Wollaston, from which it would appear that the electricity obtained in the com-

mon electrical machine is derived principally from this source. When he employed as the rubbing substance an amalgam of silver or of platina, which are metals very little subject to oxidation, he could obtain no electricity. An amalgam of tin, on the other hand, supplied a large quantity of electricity. Zinc acts still better than tin; but the best amalgam for this purpose is made with both tin and zinc, a mixture which oxidates more readily than either metal separately. As a further trial whether oxidation assists in the production of electricity, a small cylinder with its cushion and conductor was arranged in a vessel so contrived that the contained air could be changed at pleasure. After ascertaining the degree of excitement produced in atmospheric air, carbonic acid was substituted, but the excitement could not be renewed; while it was immediately reproduced on the readmission of common air. It must be acknowledged, however, that Sir H. Davy, in repeating these experiments, arrived at opposite results; for he states, that the machine acted equally well in hydrogen gas as in atmospheric air, and was even more active in carbonic acid gas, a circumstance which he attributes to the greater density of this gas.

(215.) Electricity is often developed by processes quite independent of chemical changes. This is evident from its production by the friction of two bodies of the same kind upon one another, as has been already noticed, (§ 35;) and also by the strong electricity which is manifested on the separation of the parts of the same body. Thus, if a piece of dry and warm wood be suddenly rent asunder, the two surfaces which have separated are found to be electrified, the one positively, the other negatively; and a flash of light is perceived if the experiment be made in the dark. The same phenomenon is observed when the plates of mica (Muscovy glass) are suddenly torn asunder; and even when a stick of sealing-wax is broken across; the two surfaces of fracture being in each case positive and negative respectively. Dr. Brewster discovered that the fracture of the unannealed glass tears, called *Prince Rupert's drops*, was attended with the evolution of electrical light, which pervaded the whole drop, so that its form was distinctly visible in the dark. The light appears even when the experiment is made under water.

(216.) There is every reason to presume that electricity is essentially concerned in the processes that are carried on in the living system both of animals and vegetables. In the animal economy more particularly, the operation of this agent is indicated in the processes of secretion, in the actions of the muscles and nerves, and probably, indeed, in all the vital functions. There are several kinds of fish, which are endowed with the power of accumulating large quantities of electricity, which they can discharge at pleasure through conducting bodies that come in contact with them, and thus communicate powerful shocks. This power is possessed in an eminent degree by the torpedo, which is a species of ray; but it is also met with in the Gymnotus electricus, the Silurus electricus, the Trichiurus indicus, and the Tetraodon electricus. But as this, as well as other subjects relating to animal electricity, involve considerations which properly belong to Galvanism, we must defer treating of them until this branch of electrical science is before us.

Chapter XV

Electricity of the Atmosphere.

(217.) As the subject of atmospheric electricity is more especially a branch of the science of Meteorology, we shall content ourselves, in this place, with a very brief outline of the principal facts relating to it.

(218.) The atmosphere is very generally in an electrical state. This may be ascertained by employing a metallic rod elevated to some height above the ground, and communicating at its lower end, which should be insulated, with an electroscope. In order to collect the electricity of the higher regions of the air, a kite may be raised, in the string of which a slender metallic wire should be interwoven, so as to conduct the electricity. If the electroscope be sufficiently sensible it will usually indicate the prevalence of positive electricity in the atmosphere, the intensity of which increases according as the stratum examined is more elevated. In the ordinary state of the atmosphere its electricity is invariably found to be positive: and is stronger in winter than in summer; and during the day than the night. From the time of sunrise it increases for two or three hours, and then decreases towards the middle of the day, being generally weakest between noon and four o'clock. As the sun declines its intensity is again augmented, till about the time of sun-

set, after which it diminishes, and continues feeble during the night. In cloudy weather the electrical state is much more uncertain; and when there are several strata of clouds, moving in different directions, it is subject to great and rapid variations, changing sometimes from positive to negative, and back again, in the course of a few minutes. On the first appearance of fog, rain, snow, hail, or sleet, the electricity of the air is generally negative, and often highly so; but it afterwards undergoes frequent transitions to opposite states. On the approach of a thunder-storm these alternations of the electric condition of the air succeed one another with remarkable rapidity. Strong sparks are sent out, in great abundance, from the conductor; and it becomes dangerous to prosecute experiments with it in its insulated state.

(219.) The analogy between the electric spark, and more especially of the explosive discharge of the Leyden jar, with atmospheric lightning and thunder, is too obvious to have escaped notice, even in the early periods of electrical research. It had been observed by Dr. Wall and by Gray, and still more pointedly remarked by the Abbé Nollet. Dr. Franklin was so impressed with the many points of resemblance between lightning and electricity, that he was convinced of their identity, and determined to ascertain by direct experiment the truth of his bold conjecture. A spire which was erecting at Philadelphia he conceived might assist him in this inquiry; but, while waiting for its completion, the sight of a boy's kite, which had been raised for amusement, immediately suggested to him a more ready method of attaining his object. Having constructed a kite by stretching a large silk handkerchief over two sticks in the form of a cross, on the first appearance of an approaching storm, in June 1752, he went out into a field, accompanied by his son, to whom alone he had imparted his design. Having raised his kite, and attached a key to the lower end of the hempen string, he insulated it by fastening it to a post, by means of silk, and waited with intense anxiety for the result. A considerable time elapsed without the apparatus giving any sign of electricity, even although a dense cloud, apparently charged with lightning, had passed over the spot on which they stood. Franklin was just beginning to despair of success, when his attention was caught by the bristling up of some loose fibres on the hempen cord; he immediately presented his knuckle to the key, and received an electric spark. Overcome with the emotion inspired by this decisive evidence of the great discovery he had achieved, he heaved a deep sigh, and conscious of an immortal name, felt that he could have been content if that moment had been his last. The rain now fell in torrents, and wetting the string, rendered it conducting in its whole length; so that electric sparks were now collected from it in great abundance.

It should be noticed, however, that about a month before Franklin had made these successful trials, some philosophers, in particular Dalibard and De Lors, had obtained similar results in France, by following the plan recommended by Franklin. But the glory of the discovery is universally given to Franklin, as it was from his suggestions that the methods of attaining it were originally derived.

(220.) This important discovery was prosecuted with great ardour by philosophers in every part of Europe. The first experimenters incurred considerable risk in their attempts to draw down electricity from the clouds, as was soon proved by the fatal catastrophe, which, on the 6th of August, 1753, befel Professor Richman, of Petersburg, whose name has already been before us, (§ 123.) He had constructed an apparatus for observations on atmospherical electricity, and was attending a meeting of the Academy of Sciences, when the sound of distant thunder caught his ear. He immediately hastened home, taking with him his engraver, Sokolow, in order that he might delineate the appearances that should present themselves. While intent upon examining the electrometer, a large globe of fire flashed from the conducting rod, which was insulated, to the head of Richman, and passing through his body, instantly deprived him of life. A red spot was found on his forehead, where the electricity had entered, his shoe was burst open, and part of his clothes singed. His companion was struck down, and remained senseless for some time; the door-case of the room was split, and the door itself torn off its hinges.

(221.) The protection of buildings from the effects of lightning, is the most important practical application of the theory of electricity. We have only room for a few observations on the principles on which conductors for this

purpose should be constructed. They should be formed of metallic rods, pointed at the upper extremity, and placed so as to project a few feet above the highest part of the building they are intended to secure; they should be continued without interruption till they descend into the ground, below the foundation of the house. Copper is preferable to iron as the material for their construction, being less liable to destruction by rust, or by fusion, and possessing also a greater conducting power. The size of the rods should be from half an inch to an inch in diameter, and the point should be gilt, or made of platina, that it may be more effectually preserved from corrosion. An important condition in the protecting conductor is, that no interruption should exist in its continuity from top to bottom: and advantage will result from connecting together by strips of metal all the leaden water pipes, or other considerable masses of metal in or about the building, so as to form one continuous system of conductors, for carrying the electricity by different channels to the ground. The lower end of the conductors should be carried down into the earth till it reaches either water, or at least a moist stratum.

For the protection of ships, chains made of a series of iron rods linked together, are, by their flexibility, most conveniently adapted. They should extend from the highest point of the mast some way into the sea, and the lower part should be removed to some distance from the side of the ship, by a wooden spar or outrigger.

The air of close rooms, vitiated by respiration, is found to be negatively electrified.

Chapter XVI.

Theoretical Views of the Nature of Electricity.

(222.) The preceding history of the phenomena relating to electricity, may prepare us for the discussion of some interesting inquiries concerning the real nature of this powerful and mysterious agent, and the theory of its operation.

The first question that presents itself is with respect to its materiality. Besides the well-known mechanical forces which belong to ordinary ponderable matter, the phenomena of nature exhibit to our view another class of powers, the presence of which, although sufficiently characterised by certain effects, is not attended with any appreciable change in the weight of the bodies with which they are connected. To this class belong heat, light, electricity, and magnetism: each of which, respectively, produces certain changes on material bodies, either of a mechanical or chemical nature, which it is natural to regard as the effects of motion communicated by the impulse of material agents, of so subtile and attenuated a kind, as to elude all detection when we apply to them the tests of gravity or inertia. If we admit heat and light to be material, analogy will lead us to ascribe the same character to electricity and to magnetism, notwithstanding their being imponderable.

(223.) But the materiality of electricity has also been maintained on other grounds. The pungent sensation of the electric spark, the smart blow which accompanies the shock, the vivid line of light which marks its course, the varied sounds which attend its passage through the air, and the irresistible fury with which it bursts asunder the densest textures, all seem to denote the mechanical effects of sudden and powerful impulse; all seem to imply the rushing of a stream of fluid possessed of momentum adequate to produce these energetic motions. Can we refuse to ascribe the character of materiality to that which we not only see and hear, but feel also?

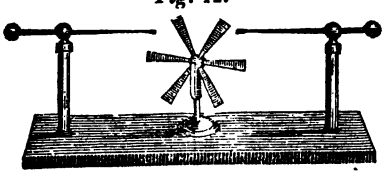
(224.) This argument has been endeavoured to be strengthened by a variety of experiments, from which the communication of impulse in a particular direction with respect to the species of electricity has been inferred. The stream of air, which proceeds from a pointed conductor when electricity is issuing from it, appears as if the air were carried forward along with the electric fluid. The direction of its motion is still more decidedly indicated by the different luminous appearances which accompany the escape of the fluid from, or its reception by, a pointed conductor. (See *fig.* 23.) We have already had occasion to notice the manner in which this curious fact appears to support the hypothesis of Franklin, implying the singleness of the electric fluid, (§ 98.)

(225.) The following experiment has also been adduced by Cavallo and by Singer, in support of the same opinion. Place on the table of the universal discharger a card bent lengthwise over a round ruler, so as to form a hollow cylindrical groove; or, what is still better two straight sticks of sealing-wax, laid parallel to each other, so that the junction of their rounded edges may form a groove. In this groove place a pith-ball

of about half an inch in diameter, and arrange the wires of the discharger with their points in the direction of the groove, and at four inches from each other, the ball being equally distant from each. On passing a small charge from one wire to the other, the ball will be driven from the positive to the negative wire, and this effect will be constant if the wires terminate in points; but if they are knobbed, the ball frequently vibrates between them, because the influence of the attracting surfaces upon the ball interferes with the regularity of the effect, and often renders the result equivocal.

(226.) The nature and place of the perforation effected in a card by the passage of an electric charge, of which we have already given an account (§ 159), appear to favour the same view of the subject. The following experiment, also, shews that the impulse is communicated most forcibly in the direction from the positive towards the negative conductor. A light float-wheel, the vanes of which are made of card paper, inserted in the circumference of a cork turning freely on a pin passed through its centre as an axle, will be put in motion by presenting to it an electrified point, apparently in consequence of the impulse of the stream of air which issues from the point. Whether the point be positively or negatively electrified, the direction of the motion, as well as of the stream of air, is always the same. But if the wheel be placed on an insulating stem, as in *fig.* 42, and introduced between the pointed

Fig. 42.

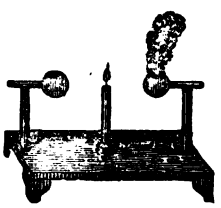


wires of the universal discharger, which are to be placed as accurately as possible opposite to each other, and at the distance of an inch or more from the upper vanes; on connecting one of the wires with the positive, and the other with the negative conductor of an electrical machine, and exciting it, the wheel will move as if impelled by a stream from the positive to the negative wire. On reversing the connections, so that the electricity of each wire is changed, the motion of the wheel will likewise be reversed.

(227.) If a card be placed vertically, by inserting it in a small piece of cork that may form a base of about a quarter of an inch wide for it to stand upon, but so that it may be overthrown by the smallest impulse; and the pointed wires of the universal discharger be brought opposite to each other, and about a quarter of an inch below the upper edge of the card, which stands at an equal distance between them; on connecting the wires with a machine, or with an insulated jar, so as to effect an electric discharge between them, the card will be thrown down, and will constantly fall from the positive, and towards the negative wire.

(228.) The determination of a stream of electrified air in this direction is also rendered very sensible by the motions of smoke or vapour placed in the circuit of the electricity. Thus the flame of a taper placed between two oppositely electrified balls will constantly be blown from the positive to the negative side. *Fig.* 43 represents two hollow metallic

Fig. 43.



balls, about three quarters of an inch in diameter, insulated on separate glass pillars, by which they are supported at a distance of two inches from each other: the upper part of each ball is hollowed into a cup, into which a small piece of phosphorus is to be put. A small candle has its flame situated mid-way between the balls, one of which is connected with the positive, and the other with the negative conductor of the machine. When the balls are electrified, the flame is agitated, and inclining towards the one which is negative, soon heats it sufficiently to set fire to the phosphorus it contains, whilst the positive ball remains perfectly cold, and its phosphorus unmelted. On reversing the connections of the balls with the machine, the phosphorus in the other ball will now be heated and will inflame.

(229.) However plausibly it may have been inferred, from a superficial view of these facts and experiments, that the electric fluid actually possesses momentum, and that it moves in a particular direction, a more rigid analysis of the phenomena will show that they in no

degree warrant such an inference. All the mechanical effects that attend the transfer of electricity are ultimately resolvable into the sudden action of a repulsive power exerted among the particles of matter which are situated in the line of its course. They are only particular instances of the fundamental law of electric action, that bodies charged with the same kind of electricity repel one another. Thus the particles of air electrified by a pointed conductor are repelled by that conductor, and repel it also; and, moreover, repel one another: and the same effect takes place whether their electric state be of the positive or negative kind. Hence the stream of air which proceeds from any electrified point is very naturally accounted for. If the quantity of electricity which is transferred is considerable, it excites a more violent commotion among the particles which it influences in its passage. The intense energy of its repulsive action produces the most sudden and forcible expansion of that portion of the air which occupies this line; this air thus expanding must be impelled laterally against the surrounding particles, and must occasion their sudden compression. The evolution of heat and light is the necessary consequence of this violent compression; and the vibratory impulse being propagated in all directions is the source of the sound which attends the electric explosion. The sensation to which the passage of the electric shock through our bodies gives rise, is also, evidently, referable to an impression made on the nerves by the same repulsive action. In all this we can discern no positive proof of the operation of a material agent extraneous to the body itself and acting by mechanical impulse. The materiality of electricity, therefore, must still rest upon a similar foundation with that of heat, or of light.

(230.) If the electric power, or fluid, if we choose to consider it as such, does not act by its mechanical momentum, the arguments in favour of the motion of a single fluid from the positive to the negative body, derived from the appearances of the streams of electric light, (§ 97, 98,) the impulsion of a pith-ball, (§ 225,) the perforation of a card, (§ 159,) the rotation of a windmill, (§ 226,) and the determination of the flame of a taper (§ 228) in one constant direction, must fall to the ground, and can evidently be of no avail in deciding the great question, whether there be two electric fluids or only one. But, still, it is incumbent upon us to inquire upon what principle these remarkable differences in the phenomena of positive and of negative electricity can be accounted for, consistently with either hypothesis.

(231.) On an attentive examination of the phenomena they appear to be explicable on the supposition that the air, or medium through which the electricity passes, is, in the language of one theory, more disposed to admit of the passage of the vitreous than of the resinous electricity; or, to speak consistently with the Franklinean theory, that it is more disposed to receive the electric fluid from a conductor which is charged with it, than to part with it to an undercharged conductor which absorbs it. The consequences of this hypothesis are, that the vitreous electricity meets with less resistance in passing out from a body into the air, and is therefore carried forward more readily and more directly than the resinous electricity. The latter, in consequence of meeting with greater resistance to its exit, is more diffused in the surrounding space.

On the Franklinean theory the same effects will follow with reference to the propulsion of the electric fluid from the positive, and its absorption by the negative body.

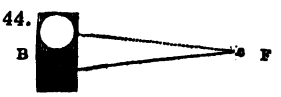
(232.) That the peculiarity of the mechanical effects of the different species of electricity depends upon the properties of the air, which is the vehicle of its agency, and not upon any specific power in the agent itself, is shown by a modification of the experiment described in § 159, in which a varnished card, suspended between two conductors, was perforated at the point where it was touched by the negative wire. On repeating the same experiment under the receiver of an air-pump, Mr. Tremery found, that in proportion as the air is exhausted, the place where the card is perforated by the electric shock approaches nearer to the positive wire. When the pressure of the air is reduced to one-half, the hole is at the middle point between the two wires. At every discharge, a flash is seen to pass from each conductor to the place of perforation. The curious appearances presented by the edges of the perforations made in the leaves of a quire of paper, already detailed (§ 160, 161,) are not reconcileable with the supposition of a mechanical impulse acting only in one direction, but indicate the equal repulsive action of both kinds of electricity, when the disturbing influence of the

air is withdrawn. It is a confirmation of this hypothesis, respecting the peculiar kind of obstruction which air opposes to the passage of electricity, that other substances have been discovered in which a similar property exists. Mr. Ermann, of Berlin, has found that the flame of alcohol is possessed of a greater conducting power with regard to positive, than to negative electricity. Alkaline soap, on the contrary, conducts negative electricity better than positive; and will, therefore, serve to insulate a feeble degree of the latter, at the same time that it permits the passage of the former.

(233.) It has always been urged as a strong objection to the theory of a single electric fluid, that it necessarily involves the condition of a mutual repulsion among the particles of ordinary matter. See § 52. Before attempting to combat this objection, it will be proper to enter into a somewhat fuller illustration of the position than we have already done; and for this purpose we shall avail ourselves of the assistance of a few diagrams, calculated to aid our conceptions of the forces concerned in the mutual actions of electrified or neutral bodies. For the sake of greater distinctness, we shall suppose the whole of the matter in the body, of which we are studying the actions, to be concentrated in a small space, and we shall represent this matter by a black square. In like manner, we shall suppose that the whole of the electric fluid contained in the same body is condensed into a small space, denoted by a white circle. The mutual actions of the matter or electric fluid in two adjacent bodies, are expressed by lines passing from the one to the other respectively; the attractions being distinguished by unbroken lines, and the repulsions by dotted lines.

(234.) *Fig.* 44 represents a body B in

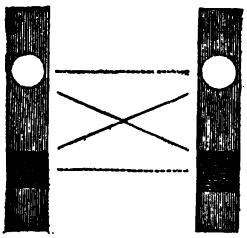
Fig. 44.



a neutral state of electricity, by which is to be understood, that the quantity of fluid it contains exists in a proportion so exactly adjusted to the quantity of matter, as that its repulsion for a particle F of electricity at any distance, precisely balances the attraction of the matter for that same particle. While this equilibrium is preserved among the forces which would impel any electric fluid external to the body both from it and towards it, it is evident that the body will neither acquire nor lose electricity, but remain quiescent, whether it be insulated or not.

(235.) The state of the forces operating between two similar neutral bodies is shown in *fig.* 45. Here it

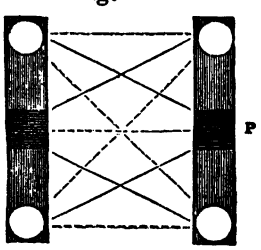
Fig. 45.



follows *from the condition of neutrality, as above defined,* that the two attractive forces, denoted by the two whole lines, are *each of them* equal to the repulsive force between the two fluids, denoted by the upper dotted line. Actuated by these forces only, therefore, the two bodies would attract each other. The addition of a second repulsive force between the two portions of matter, as represented by the lower dotted line, is therefore necessary to account for the state of equilibrium which we find, under these circumstances, really obtains. Some persons have conceived, that by assuming the repulsive force of the electric particles to be double the attractive forces of the same particles for matter, the equilibrium might be explained without having recourse to the mutual repulsion of the particles of matter: forgetting, that such an assumption is incompatible with that of the neutral state of the bodies, which is the condition under which we are now examining them.

(236.) The repulsion of two bodies, each containing twice the quantity of electric fluid requisite for the saturation of their respective matter is illustrated by *fig.* 46. All the forces represented

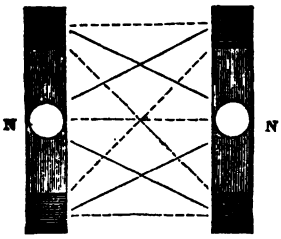
Fig. 46.



by the lines must, from the hypothesis, be regarded as equal in point of intensity: but the number of repulsive forces is as five, while that of the attractive forces is only as four: the former therefore will prevail.

(237.) Precisely the same result will obtain in the case of two negatively electrified bodies, in which, as represented in *fig.* 47, the quantity of matter

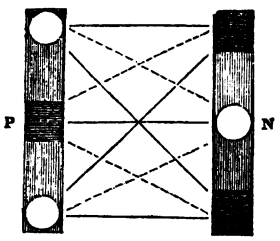
Fig. 47.



is twice as much as the fluid can saturate. In the former case it was the repulsion between the two portions of fluid which were in excess that destroyed the equilibrium; while in this case the same effect is produced by the mutual repulsion of the unsaturated portions of matter.

(238.) Lastly, we may collect from an examination of *fig.* 48, where a body

Fig. 48.



positively electrified is supposed to be placed near one that is negatively electrified, that the ultimate effect will be determined by the attraction between the fluid in excess in the former, and the unsaturated matter in the latter: all the other attractions and repulsions exactly compensating each other.

(239.) It is a great, though a common error to imagine, that the condition assumed by Æpinus, namely, that the particles of matter, when devoid of electricity, repel one another, is in opposition to the law of universal gravitation established by the researches of Newton; for this law applies, in every instance to which inquiry has extended, to matter in its ordinary state, that is, combined with a certain proportion of electric fluid. By supposing, indeed, that the mutual repulsive action between the particles of matter is, by a very small quantity, less than that between the particles of the electric fluid, a small balance would be left in favour of the attraction of neutral bodies for one another, which might constitute the very force which operates under the name of gravitation: and thus both classes of phenomena may be included in the same law.

(240.) An objection has been urged by Biot against the hypothesis of a single fluid, on the ground that it implies an equal degree of attraction between the fluid and every species of matter, whereas in the case of other agents, such as heat and magnetism, the degree of their attraction is very different towards different kinds of matter. This objection does not apply to the hypothesis of the two fluids, for they are assumed as acting independently of any specific attractions for the bodies which contain them: hence their distribution in those bodies follows the same law, whatever be the specific nature of the materials of which the latter are composed.

(241.) We arrive, then, at the conclusion that there is no fact in electricity which cannot be explained on either of the two hypotheses: but to which side the balance of probabilities may incline, when the respective merits and demerits of each are taken into account, remains, perhaps, to be decided more by the taste than the judgment of the inquirer.

GALVANISM.

Chapter I.

Origin of Galvanism.

(1.) The term Galvanism is employed to designate a peculiar form of electric agency, elicited under particular circumstances, and capable of producing certain effects on bodies, not usually resulting from the ordinary modes of excitation. The first notice that we find of any phenomenon referable to this branch of electricity, occurs in a metaphysical work, published in 1767, and entitled, *The General Theory of Pleasures*, by a German writer of the name of Sulzer, who observed, that by applying two metals, one above, and the other below the tongue, and then bringing them into contact, a peculiar taste was perceived. He ascribed this sensation to some vibratory motion, excited by the contact of the metals, and communicated to the nerves of the tongue. Content with this loose and fanciful explanation, Sulzer appears to have pursued the inquiry no farther; and the curious fact he had announced remained for many years unnoticed, until the attention of the philosophic world was drawn to the subject, by the discovery of Galvani. Important discoveries in science seem often to arise from accident; but, on closer examination, it is found that they always imply the exercise of profound thought. As the fertility of the soil is essential to the germination and growth of the seed which the wind may have scattered on its surface, so it is principally from the qualities of mind in the observer that an observation derives its value, and may be made eventually to expand into an important branch of science. This has been remarkably exemplified in the origin of galvanism. Its founder, Galvani, was professor of anatomy at Bologna, and had early distinguished himself by his attainments and his zeal in his profession, and especially by the ardour with which he cultivated comparative anatomy. It happened, in the year 1790, that his wife, being consumptive, was advised to take, as a nutritive article of diet, some soup made of the flesh of frogs. Several of these animals, recently skinned for that purpose, were lying on a table in the laboratory, close to an electrical machine, with which a pupil of the professor was amusing himself in trying experiments. While the machine was in action, he chanced to touch the bare nerve of the leg of one of the frogs with the blade of the knife that he held in his hand; when suddenly the whole limb was thrown into violent convulsions. Galvani was not present when this occurred, but received the account from his lady, who had witnessed, and had been struck with the singularity of the appearance. He lost no time in repeating the experiment, in examining minutely all the circumstances connected with it, and in determining those on which its success depended. He ascertained that the convulsions took place only at the moment when a spark was drawn from the prime conductor, and the knife was at the same time in contact with the nerve of the frog. He next found that other metallic bodies might be substituted for the knife; and very justly inferred that they owed this property of exciting muscular contractions to their being good conductors of electricity.

(2.) Far from being satisfied with having arrived at this conclusion, it only served to stimulate him to the further investigation of this curious subject; and his perseverance was at length rewarded by the discovery, that similar convulsions might be produced in a frog, independently of the electrical machine, by forming a chain of conducting substances between the outside of the muscles of the leg, and the crural nerve. Galvani had previously entertained the idea that the contractions of the muscles of animals were in some way dependent on electricity; and as these new experiments appeared strongly to favour this hypothesis, he with great ingenuity applied it to explain them. He con-

pared the muscle of a living animal to a Leyden phial, charged by the accumulation of electricity on its surface; while he conceived that the nerve belonging to it performed the function of the wire communicating with the interior of the phial, which would, of course, be charged negatively. In this state, whenever a communication was made, by means of a substance of high conducting power, between the surface of the muscle and the nerve, the equilibrium would be instantly restored, and a sudden contraction of the fibres would be the consequence.

(3.) The discoveries of Galvani were no sooner made known to the scientific world, than they excited very general interest; and philosophers in every country in Europe vied with each other in repeating his experiments, in varying them in all possible ways, and in inventing all kinds of hypotheses to account for the phenomena. Some regarded them as the effects of a new and unknown agent, differing altogether from electricity; while others, adopting the views of Galvani, recognised them to be electrical, but attributed them to a peculiar modification of that power, residing in the animal system only, and which they accordingly distinguished by the name of *Animal Electricity*. But the discovery of new facts contributed more and more to multiply and strengthen the analogies between galvanism and electricity: till at length all doubt of the identity of the agent concerned in all these phenomena was removed by the discovery of the *Galvanic*, or *Voltaic Pile*.* Whatever share accident may have had in the original discovery of Galvani, it is certain that the invention of the pile, an instrument which has most materially contributed to the extension of our knowledge in this branch of physical science, was purely the result of reasoning. Professor Volta of Pavia, a name already familiar to electricians,* was led to the discovery of its properties by deep meditation on the developement of electricity at the surface of contact of different metals.† We may justly regard this discovery as forming an important epoch in the history of galvanism: and indeed, since that period, the terms, *Voltaism*, or *Voltaic Electricity*, have often, in honour of this illustrious philosopher, been used to designate that particular form of electrical agency, which is the subject of the present treatise.

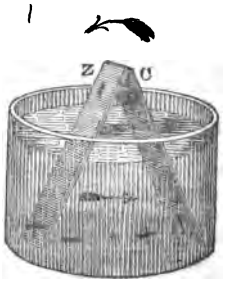
Previously to our entering into a detailed exposition of the facts relating to this science, and of the theories which have been proposed for their explanation, it will be necessary to direct our attention to the nature of those arrangements of bodies, which are the sources of galvanic power.

Chapter II.

Simple Galvanic Circles.

(4.) The process usually adopted for obtaining galvanic electricity is to interpose between two plates of different kinds of metal a fluid capable of exerting some chemical action on one of the plates, while it has no action, or at least a different one, on the other plate: and then to establish a communication between the plates at some other part, either by their direct contact with one another, or by the intervention of conducting substances. Let us take, for example, a plate of zinc, Z, and another of copper, C, (*fig.* 1.) and immerse

Fig. 1.



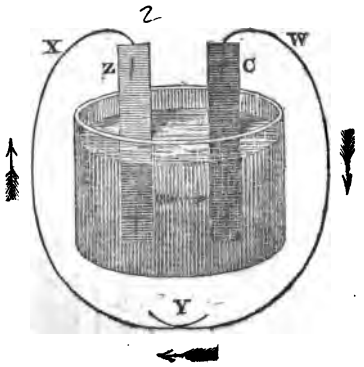
them, to a certain depth only, in diluted sulphuric acid, A, contained in a glass vessel, keeping their lower edges at a little distance from one another: then, inclining them towards each other, let us bring their upper edges, which are out of the fluid, into contact, as represented in the figure. The arrangement we have thus formed constitutes what is called a *galvanic circle*, in its simplest form, of which the three parts, or elements, are zinc, acid, and copper; each of these bodies being in contact with the two others. Under these circumstances it is found that a quantity of electricity is set in motion; a continued current of electric fluid passing from the zinc to the

* See *Treatise on Electricity*, § 192, 193.
† Ibid. § 203.

acid—from the acid to the copper—from the copper back again to the zinc—and so on, in a perpetual circuit. Such at least must be the explanation of the phenomena on the hypothesis of Franklin, implying the singleness of the electric fluid. But if the theory of Du Fay, which recognises two different fluids, be adopted, what has just been stated must be understood to refer exclusively to the current of vitreous electricity. Now, according to that theory, every such transfer of electricity consists of an interchange of the two fluids: the current of vitreous electricity just mentioned, must, therefore, necessarily be accompanied by an opposite current of resinous electricity; that is, of one flowing from the zinc to the copper; from the copper to the acid; and from the acid to the zinc. Hence in our future explanations of the phenomena of galvanism, it will be sufficient to express the former of these currents only; provided we bear in mind that the transfer of any quantity of vitreous electricity in a given direction, implies the transfer of an equal quantity of resinous electricity in the opposite direction.

(5.) The same effects will take place, if, instead of allowing the metallic plates to come in direct contact, the communication betwen them be effected by wires, (as shewn in *fig.* 2.) extending from the

Fig 2.



one to the other. The circuit of electricity will thus be lengthened, but the currents will move in the same direction as before; that of the positive electricity being denoted in the figure by the position of the arrows; namely, in the fluid, from the zinc towards the copper; and along the wires, from the copper to the zinc. The completion of the circuit by means of wires, enables us to direct the electric current through such bodies as we may wish to subject to its operation, and at the same time gives us the power of interrupting or renewing at pleasure the communication between the two metallic plates, by merely separating or joining together their remote extremities at Y. When united, the wire W, which proceeds from the copper-plate C, is imparting electricity to the wire X, which touches the zinc plate Z; hence, the former is considered as being in a positive, and the latter in a negative state.

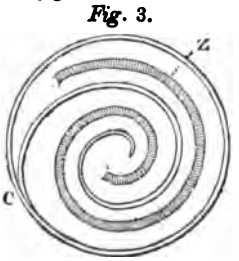
(6.) The electrical effects of the simple apparatus just described are, in general, too feeble to be perceived, unless by very delicate tests. The fact mentioned by Sulzer, and the experiments of Galvani on the muscles of frogs, in their original form, afford, however, examples of the operation of simple galvanic circles. When the tongue is interposed between zinc and copper, the saliva in contact with the metals performs the part of the acid in the experiment above mentioned, and the stream of electricity in its passage from the zinc to the copper, through the substance of the tongue, affects the nerves of that organ, so as to give rise to sensations of taste. In Galvani's experiment, muscular contractions were produced by forming a connection between two different metals, one of which was applied to the nerve, and the other to the muscles of a frog's leg. It is evident that such an arrangement composes a galvanic circle, deriving its activity from the chemical properties of the fluids in those parts of the frog that are in contact with the metals. Although the quantity of electricity set in motion by this slight action, must be supposed to be exceedingly minute, it is yet sufficient, when passing over the exquisitely sensible nerves of the tongue, or through the highly irritable fibres of a frog, to produce a very considerable impression.

(7.) It has even been found possible, by means of a very small galvanic circle of the same simple kind as that which we have described, to produce some of the more energetic effects of galvanism, such as raising the temperature of the wire which conducts it to a red heat. We are indebted to the ingenuity of Dr. Wollaston for the contrivance of an apparatus, which he calls an *elementary galvanic battery*, capable of exhibiting

this effect.* He found that a single plate of zinc, of the size of a square inch, when properly mounted, and suspended in dilute sulphuric acid, between two copper plates of similar dimensions, was more than sufficient to ignite a wire of platina, one three-thousandth of an inch in diameter, which formed part of the connection between the two metals.

(8.) It will readily be conceived, that by enlarging the size of the plates, their power will be proportionally increased. The first battery of this kind, on a very large scale, was that constructed by Dr. Hare, professor of chemistry in the university of Philadelphia, and called by him a *Calorimotor*, from its remarkable power of producing heat.† It consisted of sheets of zinc, and of copper, formed into coils, so as to encircle each other, separated only by interstices of a quarter of an inch in width. This construction is shown in *fig.* 3, which exhibits a horizontal section of the plates as they are coiled together: the thick line Z, representing the zinc, and the thinner line C, the copper plate. The zinc sheets were nine inches by six; the copper fourteen by six; more of the latter metal being required; as in every coil it was made to commence within the zinc, and completely to surround it on the outside. Each coil was about two inches and a half in diameter; their number amounted to 80; and by means of a lever they could all be let down at the same moment into as many glass jars, two inches and three quarters diameter inside, and eight inches high, placed so as to receive them, and containing the acid liquor intended to act upon the zinc.

Fig. 3.



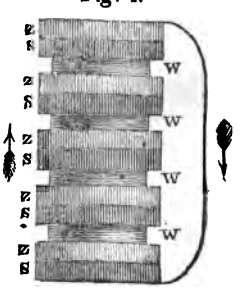
(9.) To the class of simple galvanic circles must also be referred the magnificent battery belonging to the London Institution, and which was constructed under the direction of Mr. Pepys.* It consists of two plates only, the one of zinc, and the other of copper, coiled round a cylinder of wood, and prevented from coming into contact by ropes of horse hair, which is a non-conducting substance, interposed in various places between them. The length of each plate is 60 feet, and its breadth two feet; the total surface being 400 square feet. In order to charge this battery, the whole coil is immersed in a tub containing acid of the proper strength.

Chapter III.

Compound Galvanic Circles.

(10.) Many of the effects of galvanism require for their production the combined influence of a number of plates, arranged so as to form what is termed *a compound galvanic circle.* To this class belongs the galvanic pile, discovered by Volta, and announced by him in a paper which he transmitted, in the year 1800, to the Royal Society. He had been led by theory to conceive that the effect of a single pair of metallic plates might be increased indefinitely by multiplying their number, and disposing them in pairs, with a less perfect conducting substance interposed between each pair. For this purpose he provided an equal number of silver coins, and of pieces of zinc, of the same form and dimensions; and also circular discs of card, soaked in salt water, and of somewhat less diameter than the metallic plates, Of these he formed a pile or column, as shown in *fig.* 4: in which the three substances, silver,† zinc, and wet card, denoted by the letters S, Z, and W, were

Fig. 4.



* See Thomson's *Annals of Philosophy*, vol. vi. p. 209. While these pages were in the press we have sustained an irreparable loss in the death of Dr. Wollaston, a philosopher whose unrivalled acuteness of observation, soundness of judgment, and integrity of mind, directed to the highest objects of science, place his name among the most eminent of its benefactors.

† Silliman's *Journal*, iii, 105, and *Annals of Philosophy*, New Series, i. 330.

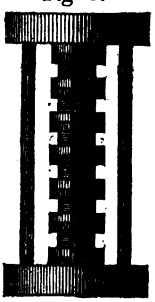
* *Philosophical Transactions* for 1823, p. 187.

† Copper might have been used instead of silver, as in the single galvanic circle already described (§ 4, 5.) with the same effect.

made to succeed one another in the same regular order throughout the series. The efficacy of this combination realized the most sanguine anticipations of the discoverer: it far exceeded in power the single circle already described. If the uppermost disc of metal in the column be touched with the finger of one hand, previously wetted, while a finger of the other hand is applied to the lowermost disc, a distinct shock is felt in the arms, similar to that from a Leyden phial, or still more nearly resembling that from an electrical battery weakly charged. A repetition of shocks is obtained for an indefinite period, whenever the circuit is completed by touching the two ends of the pile with the moistened fingers. The strength of the shock is, as might be expected, greater in proportion to the number of plates of which the pile is composed.

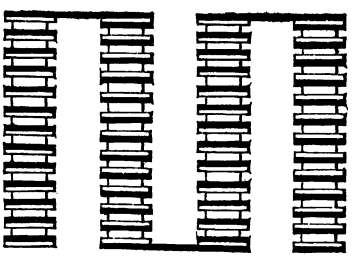
If the pile were raised to any considerable height, it would obviously be in danger of oversetting: this may be prevented by placing the discs between three vertical glass rods, properly varnished, and cemented into two thick pieces of wood, one of which serves as a base, and the other as a cover to the pile. See *fig.* 5.

Fig. 5.



(11.) Any number of these piles may be combined so as to form a battery, by making a metallic communication between the last plate of the one and the first of the next, and so on; taking care that the order of succession of the plates in the circuit be preserved inviolate, as is shown in *fig.* 6, where the dark

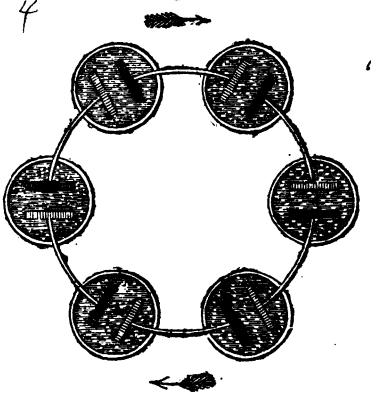
Fig. 6.



lines represent the copper, and the light lines the zinc plates.

(12.) The component parts of the pile may be arranged in a form somewhat different from the preceding, and corresponding more nearly to the elementary galvanic circle in its simplest state already described (§ 4, 5). In this new arrangement the metallic plates, instead of being piled one above the other, are placed side by side in a vertical position, and combined together in pairs, consisting each of one zinc and one copper (or silver) plate, connected at their upper edges by slips of metal, passing from the one to the other. A sufficient number of glasses being provided, and filled with water, or some acid or saline solution, they are to be placed side by side, so as to form a circle. The two plates belonging to each pair are then to be immersed in the fluids contained in two different, but adjoining, glasses; the zinc plate, for instance, in the first glass, and the copper in the second. The plates of the second pair must be immersed, in a similar way, in the second and third glasses; and so on successively throughout the series, taking care to preserve the same order of alternation in the metals. It is evident that by this arrangement, (of which an horizontal section is shown in *fig.* 7, where the dark

Fig. 7.

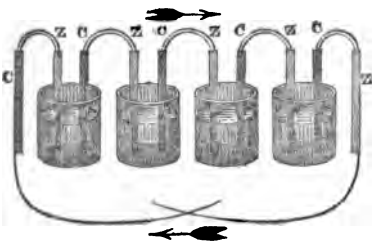


lines indicate the copper, and the lighter lines the zinc plates in each pair,) each vessel will contain one plate of zinc and one of copper, which, as they belong to different pairs, are not connected together, except through the medium of the intervening fluid in that particular vessel.

(13.) The first apparatus of this kind was constructed by Volta, who employed for that purpose a circular series of cups, and hence gave it the name of

Couronne de tasses. If the circuit be interrupted at any one point, by removing one or more of the vessels, the instrument is rendered similar in its operation to the pile, and the metallic plates at each end of the series which are not immersed in fluid, may be connected together by means of wires in order to complete the circuit. Such an arrangement is shown in *fig.* 8, where the zinc

Fig. 8.



and copper plates are marked respectively with the letters Z and C: and the course of the electric fluid denoted by the arrows.

(14.) It is also to be observed, that in every compound galvanic circle, such as is exemplified in this apparatus, the direction of the electric current is precisely the same as in a simple galvanic circle composed of the same elements. In the present case, where zinc and copper are the metals employed, and the fluid acts upon the former so as to oxidate it, a stream of positive electricity is continually circulating from the zinc to the copper plate contained in the same vessel, through the oxidating fluid which separates them; and is transferred from the copper to the zinc plate contained in the next vessel, along the slip of metal which connects them. Following its course in this manner to the end of the series, we find the electric current passing on from the last copper plate, contained in the last vessel, to the zinc plate connected with it, and thence conveyed along the wires of communication, round to the copper plate at the other end of the series. The direction of this current is shown in the figure by the arrows above and below. It is evident, therefore, that that end of the battery which is terminated by a zinc plate is that from which electricity is given out to the wire, and is, consequently, the positive end, or *pole*, as it is called, of the battery. For the same reason, the opposite end, or that terminated by the copper plate, and which receives the electricity from the wire, is the negative pole. The same observations apply to the galvanic pile; the zinc end being the positive, and the copper (or silver) end the negative pole.

(15.) It will be perceived that the denominations of the zinc and copper ends of the pile or compound battery, as being positive and negative, are exactly the reverse of what obtains in the single galvanic circle, where, as we have seen, it is the copper plate which is positive, and the zinc negative, with relation to the communicating wires. But as the direction of the electrical currents is the same in the compound as in the simple circle, this contrariety in the qualities of the poles appears, at first sight, paradoxical. But the difficulty vanishes when we advert to the circumstance, that in the simple galvanic circle the conducting wire communicates directly with that plate which is in contact with the fluid part of the apparatus; while in the compound circle it proceeds, not from the plate immersed in the fluid, but from that which is associated with it, and, therefore, of a different kind. The compound circle reduced to its condition of greatest simplicity would be represented by the following series, consisting of five parts, namely,

copper—zinc—fluid—copper—zinc.

In this arrangement the copper end is negative, and the zinc end positive. By merely removing the two terminal plates,* which, in fact, are no ways concerned in the effect, we bring it to the state of the single circle, consisting simply of

zinc—fluid—copper:

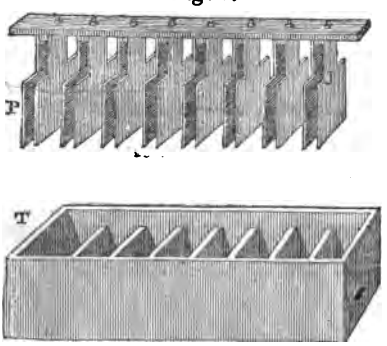
here we find the zinc end negative, and the copper end positive. It is highly necessary to possess clear ideas of this difference, since much ambiguity has arisen from inattention to it in describing experiments, and reasoning upon their results, more especially in the study of electro-magnetism, hereafter to be considered.

(16.) A much more compendious form may be given to a battery constructed on the principle of the *Couronne de tasses*, by employing a trough divided into numerous compartments by partitions, the whole being made of non-conducting materials. This will admit of the plates being brought nearer to each other, and of a much greater number

* Volta, in conformity with the theory he had adopted, considered these terminal plates as adding to the galvanic power. But we shall afterwards point out the incorrectness of that theory.

being contained in a given space. The zinc and copper plates are united in pairs, as before, by a slip of metal passing from the one and soldered to the other: each pair being placed so as to enclose a partition between them, and each cell containing a plate of zinc connected with the copper plate of the succeeding cell, and a copper plate joined with the zinc plate in the preceding cell. Such an apparatus is called a *trough battery*, and is represented in *fig.* 9.

Fig. 9.

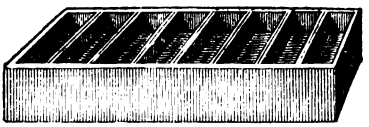


The trough, T, may be made of baked mahogany, with partitions of glass: but it is found more convenient to construct the whole of one material, and Wedgwood ware answers best for this purpose. Each trough is usually fitted up with ten or twelve cells. The plates, P, adapted to them, are connected together by a slip of baked wood, so as to allow of their being let down into the cells, or lifted out, together. A further advantage arises from this construction, that the plates and the fluid being independent of each other, the former may be readily cleaned or replaced, when worn or injured, without disturbing the fluid: and the latter may, in like manner, be removed and changed with the utmost facility. A number of these troughs may be combined with great ease, by connecting together the terminal plates of the adjoining troughs, by slips of copper; taking care, as in the case of the pile, (§ 11.) to preserve throughout the whole series the same order of alternation in the plates, by connecting the zinc end of one battery with the copper end of the next.

The voltaic battery belonging to the Royal Institution, which is of immense power, is constructed on the plan above described, and consists of 200 separate parts, each part composed of ten double plates, and each plate containing thirty-two square inches. The whole number of double plates is 2000, and the whole surface 128,000 square inches.

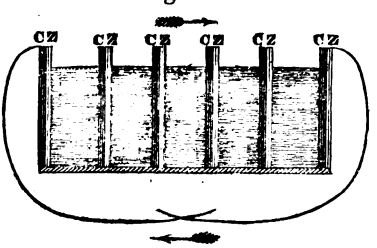
(17.) A trough battery on another construction was invented by Mr. Cruickshanks, and is represented in *fig.* 10. Plates of zinc and of copper,

Fig. 10.



united by their flat surfaces by soldering, are employed to form the partitions themselves, and are fixed into grooves in the sides of a trough of baked wood, which is a bad conductor of electricity, so as to leave sufficient intervals to hold small quantities of fluid. They must, of course, be arranged so that all the zinc surfaces shall be on one side, and all the copper surfaces on the other. The battery is charged by filling the cells with a saline solution, or with dilute acid, and the galvanic circuit completed by bringing the two wires proceeding from the ends of the battery in contact with one another. The section, *fig.* 11,

Fig. 11.



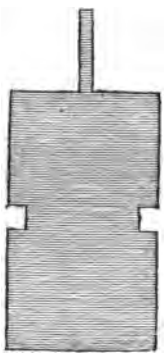
will tend to elucidate the principles of its action. Troughs of this construction, however, are exceedingly liable to get out of order, from the action of the liquid on the wood, which it tends to warp. The plates require to be fixed into the grooves by cement, in order to render them water tight; but this cement is apt to crack from the warping of the wood, and other causes, and the liquid insinuating itself into the fissures, impairs the power of the instrument by destroying the insulation of the cells.

(18.) The power of a battery is considerably increased when both surfaces of each plate of zinc, in contact with the oxidating fluid, are opposed to a surface of copper. In order to accomplish this,

it will be necessary to add a second copper plate to each pair, so that every cell may contain one zinc and two copper plates, the former being placed between the latter. This plan, which was suggested by Dr. Wollaston, was adopted by Mr. Children in the construction of a very large battery, in which each plate was six feet long, by two feet eight inches broad, so that it presented thirty-two square feet of surface.*

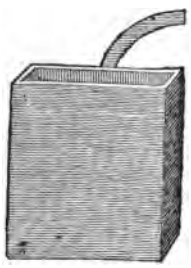
(19.) An ingenious application of this principle was made by Mr. Hart of Glasgow, in the construction of a galvanic battery, requiring no other material for confining the fluid, than the metals themselves which form the circles. This he accomplished by converting the double copper plates into cells, by adding sides and bottoms, so as to enable them to hold the acidulous fluid into which the zinc plates are immersed. The cells are formed by cutting a sheet of copper into the form shown in *fig.* 12.† They are then folded

Fig 12.



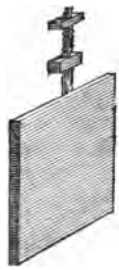
up as seen in *fig.* 13, and the seams

Fig. 13.



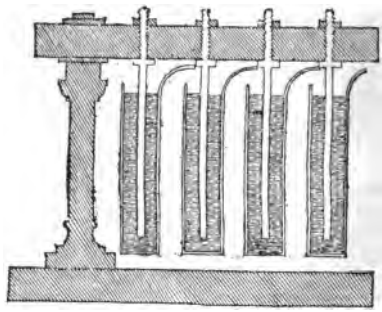
grooved. A drop of tin is run into each lower corner to render the cells perfectly tight. *Fig.* 14 represents the zinc

Fig. 14.



plate, having a piece of screwed brass-wire cast into the top of it for the purpose of suspension. *Fig.* 15 is a section

Fig. 15.



of the battery, showing how the copper tail of the first cell is connected with the zinc plate of the second, and so on. The connexion is rendered perfect by joining them with a drop of solder. Each zinc plate is kept firmly in its place by three small pieces of wood. The whole series is then fixed, by means of screw-nuts fitted on to the brass wires, to a bar of baked wood, previously well varnished. When the battery is to be used, it must be lifted off the frame, and dipped into a wooden trough, lined with lead, containing the acid. It is then placed on the frame and is ready for action. Such a battery, with an equal number of zinc plates, is found to possess considerably greater power than the best batteries of the ordinary construction.*

(20.) Various contrivances have been employed for converting a compound voltaic battery, consisting of a certain number of alternations of plates, into a

* *Philosophical Transactions* for 1815, p. 363.

† The engraving fig. 12, is here reduced in its dimensions from the original drawing. It should have been of the size required to form, when folded, the cell represented in fig. 13.

* *Edinburgh Journal of Science*, iv. 19.

battery having a smaller number, or even into one corresponding in principle to the simple battery with a single pair of plates, such as the calorimotor. These changes may be effected by altering the connexions of the plates, and uniting several plates of the same metal together, so that they may act as only one plate; or if the effect of a calorimotor be desired, connecting all the zinc plates together, and also all the copper plates, so that the whole may act only as a single pair.

CHAPTER IV

Effects of Galvanism.

(21.) THERE are three principal circumstances in which the electricity produced by the voltaic battery differs from that obtained from the ordinary electrical machine; first, the very low degree of intensity in which it exists in the former, when compared with the latter; secondly, the very large quantity of electricity which is set in motion by the voltaic battery; and thirdly, the continuity of the current of voltaic electricity, and its perpetual reproduction, even while this current is tending to restore the equilibrium. The effects of the voltaic pile have been compared by the inventor of that instrument to those of an electric battery of large dimensions, but charged only to a low degree; in which case, as appears from what has already been said on this subject in the Treatise on Electricity, a large quantity of electricity may be contained, with a very small tendency to escape, or, in other words, with a very feeble intensity. The comparison is, in many respects, just; but it fails in regard to the third property we have noticed as belonging to the voltaic apparatus; namely, the continuity of the current arising from its perpetual reproduction and circulation.

However considerable may be the power collected in a highly charged electric battery, the whole of that power is at once expended as soon as the circuit is completed. Its action may, while it lasts, be sufficiently energetic; but it is exerted only for an instant; and, like the destructive operation of lightning, can effect, during its momentary passage, only sudden and violent changes, which it is beyond the power of the experimentalist to regulate or control. On the contrary, the voltaic battery continues, for an indefinite time, to develop and supply vast quantities of electricity, which, far from being lost by returning to their source, circulate in a perpetual stream, and with undimished force. The effects of this continued current on the bodies subjected to its action, will, therefore, be more definite, and will be constantly accumulating; and their amount will, in process of time, be incomparably greater than even those of the ordinary electrical explosion. We shall accordingly find that changes in the composition of bodies are effected by galvanism which can be accomplished by no other means. Hence may be conceived the advantages which have accrued to science from the acquisition of an instrument of such vast power, and admitting of such extensive application in the wide field of chemical research.

It will be convenient to study the effects of galvanism in their relation to the three circumstances which have been noticed as characterizing its operation when contrasted with those of ordinary electricity.

§ 1. *Ordinary Electrical effects resulting from Galvanism.*

(22.) The degree of intensity in which the electricity developed by a single galvanic circle exists, is so extremely low, that its action produces none of the usual phenomena exhibited by the common electrical machine. Even from the largest calorimotor that has yet been constructed, it is not possible to obtain indications of electrical attraction and repulsion, such as are given by the feeblest degree of excitation to a piece of sealing-wax. With a few alternations of plates and interposed fluid, as in the pile or trough battery, electrical indications may be obtained, by means of an ordinary condenser. It is necessary in these experiments to advert to the distinction already pointed out (§ 15.) between single and compound circles as to the denomination of the extremities or poles of the battery. In the compound circles the zinc side is found to be positive and the copper negative. When fifty pairs of plates are employed, a delicate gold-leaf electrometer will be affected, without the aid of the condenser, and with a series of one thousand groups, even pith balls are made to diverge. In order to exhibit these ef-

fects, the wire proceeding from one extremity of the battery should be connected with the foot of the electrometer; while the wire proceeding from the opposite extremity is made to touch the cap. It was by means of the revolving doubler (see Electricity, § 195.) that the electrical states of the two ends of the voltaic pile were first ascertained by Messrs. Nicholson and Carlisle.*

(23.) Since the ends of the two wires, which proceed from the two poles of the voltaic battery, are in opposite states of electricity, we might naturally expect that they would attract one another. Such an attraction actually does take place, as Biot found by experiment;† but it does not become sensible, unless a battery composed of a great number of plates is employed.

(24.) The general conclusion deducible from the facts that have now been stated, is that the intensity of the electricity developed by galvanic combinations is increased, according as the number of alternations in the elements which compose them is greater, and that it bears no proportion to the magnitude of their surfaces.

(25.) If the voltaic battery be of sufficient size, its electricity may be transferred to a common electrical battery, which will then become charged to the same degree of intensity. Nothing more is necessary for this purpose than to connect the outer and inner coatings of the electrical battery, respectively, with the two poles of the voltaic battery; when the charge will be instantly communicated to the former. If on removing it from the voltaic battery this electricity be discharged, and the same communications be renewed, a similar charge will again be received; and the same process may be repeated an indefinite number of times. If, instead of removing the electrical battery, we allow it to remain connected with the voltaic battery, a rapid succession of sparks may be obtained from it by connecting a wire with the outer coating, and repeatedly striking the knob of the phial with the other end of the wire. If the series of plates in the voltaic battery consist of three or four hundred alternations, these rapid explosions are so powerful as to ignite the end of the wire, if it be of iron, and to cause it to throw off an abundance of sparks, consisting of small particles of iron in a state of intense combustion. With a series of one thousand, each discharge is attended with a sharp sound, and will burn thin metallic leaves. This is the more remarkable as the same voltaic battery may not have sufficient power to produce these effects by itself, or unconnected with an electrical battery. The shortest possible contact with the voltaic battery is sufficient for giving the whole of the charge which it is capable of communicating. This was apparent in some experiments made by Van Marum and Pfaff with a battery having 137½ square feet of coated surface, and which was charged to the same degree of intensity as the pile with which it was made to communicate, by a contact which did not last for the twentieth part of a second.*

§ 2. *Luminous effects of Galvanism.*

(26.) It is only when the electricity of a voltaic battery possesses a sufficient intensity, that it becomes capable of passing through air. With the calorimotor the intensity is too feeble to enable it to traverse the smallest perceptible interval between metallic conductors, so that they must be brought into actual, or at least apparent, contact, before any sensible effect is produced. In a pile or trough battery, on the other hand, composed of a considerable number of alternations of plates, on bringing together the wires from the opposite poles, the transfer of electricity begins while they are yet at a sensible distance from one another: and as in the case of ordinary electricity, this transit through the air is accompanied by vivid light. The sparks occur every time the contact between the wires is broken, as well as when it is renewed. This phenomenon, which does not take place with the electricity furnished by the ordinary means, is characteristic of voltaic electricity, and is a consequence of its continuous supply. The stream continues to flow, notwithstanding the interruption to the line of circuit, and as long as the conductors remain within the striking distance; and although this happens only for an instant, there is still sufficient time for the appearance of a spark.

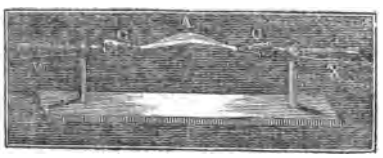
(27.) The most splendid exhibition of electric light is that obtained by placing pieces of charcoal, shaped like a pencil,

* Nicholson's *Journal*, 4to. iv. 174.
† Biot, *Traité de Physique*, ii. 511.

* *Annales de Chimie*, xl. 289.

at the ends of the two wires in the interrupted circuit, and bringing their points into contact. When the experiment was tried with the powerful battery of the Royal Institution, already noticed (§ 16.), a bright spark passed between the two points of charcoal, when they came within the distance of the thirtieth or fortieth of an inch; and immediately afterwards more than half of each pencil of charcoal, the length of which was one inch, and the diameter one-sixth of an inch, became ignited to whiteness. By withdrawing the points from each other, a constant discharge took place through the heated air, in a space at least equal to four inches, forming an arch of light in the form of a double cone, of considerable breadth, and of the most dazzling brilliancy. This phenomenon is represented in *fig.* 16; in

Fig. 16.



which W, X, are the conducting wires communicating with the ends of the battery; C, C, the pieces of charcoal, and A the luminous arch of electrical light, making the passage of electricity through the air. When any substance was introduced into this arch, it instantly became ignited: platina melted in it, as wax in the flame of a candle: some of the more refractory substances, as quartz, the sapphire, magnesia, and lime, all entered into fusion: fragments of diamond, and points of charcoal and of plumbago quickly disappeared, and seemed converted into vapour, even when the connection was made in highly rarefied air, and apparentlywithout having undergone previous fusion. When the pieces of charcoal were placed in the receiver of an air-pump, in proportion as the air was abstracted, the distance at which the discharge took place increased: and when the height of the mercury in the barometrical gage was only one quarter of an inch, the sparks were nearly half an inch in length; and by then withdrawing the points from each other, the discharge passed through a space of six or seven inches, producing a most brilliant coruscation of purple light. The whole of the charcoal became intensely ignited, and some platina wire attached to it melted with bright scintillations, and fell down in large globules.* A battery of a hundred pair of plates of six inches square will suffice to exhibit these phenomena on a smaller scale. Charcoal, carefully prepared from some of the harder woods, such as beech, lignum vitæ, or box wood, answers best for these experiments. The arched form of the stream of light passing between the two charcoal points is perceptible even when the points are within half an inch of each other.

The light obtained by voltaic electricity in the manner now described exceeds in intensity any other that art can produce. It often exhibits in succession a variety of the prismatic colours; and supplies some of the rays which are deficient in the solar beams. It is so dazzling as to fatigue the eye even by a momentary impression; and it effaces, by its superior lustre, the light of lamps in an apartment otherwise brilliantly illuminated, and which, on the sudden cessation of the galvanic light, appears for a short time as if left in darkness. It is a light which so nearly emulates the brightness of the sun's rays, as to be applicable for the purpose of illuminating objects in a solar microscope; and even with the magic lantern it has been found capable of exhibiting on a large scale, as was done by Mr. W. Allen in his lectures, all the pleasing and endless variations of the kaleidoscope.

(28.) The employment of charcoal in these experiments might lead to a suspicion that the light might, in part at least, arise from combustion; but many circumstances concur to prove that it is quite independent of this cause. During the continuance of the light, although the charcoal be in a state of ignition, yet it suffers but little loss of weight. The light is evolved with equal splendour when the experiment is made in gases that contain no oxygen, such as azote or chlorine, and in which therefore combustion could not be maintained: and it is moreover found that during the ignition, neither the gas nor the charcoal has undergone any chemical change.† Light from voltaic electricity may also be obtained, though with diminished in-

* Davy's *Elements of Chemical Philosophy*, p. 152.

† Children, *Philosophical Transactions for* 1815, p. 369.

tensity, under water, alcohol, ether, oils, and other fluids of inferior conducting power.

§ 3. *Evolution of Heat by Galvanism.*

(29.) The evolution of heat is one of the effects which accompany the action of the voltaic, as well as of the electric battery; but there is a remarkable difference in the circumstances which favour its production in the two cases. In the common electrical apparatus, heat is not sensibly evolved where the electricity moves with perfect freedom, but only when some resistance is opposed to its passage, and when there is a sudden restoration of its equilibrium accompanied with light and sound. But in the voltaic battery, an elevation of temperature is observed to take place when the circuit remains complete, when no light is evolved, and when the stream of electricity is conducted in the most silent manner. That the mere passage of voltaic electricity through bodies raises their temperature, is proved by making a wire, forming part of the circuit, pass through a known quantity of water, contained in a vessel, with a thermometer immersed in the fluid. The heat acquired by the water soon becomes sensible by the rise in the thermometer, which even attains the boiling point; and the water continues in ebullition as long as the experiment is continued.

(30.) The circulation of voltaic electricity produces an elevation of temperature, not only in that part of the circuit which connects together the poles of the battery, but also in the battery itself, every part of which, both the plates of metal and the fluid in the cells, become heated when the apparatus is in an active state. But the elevation of temperature is found not to be equal throughout the series; and the difference is dependant on causes which have not yet been accurately determined. Mr. John Murray found a gradual increase of temperature in the successive cells from the negative to the positive pole; and when a number of different troughs were joined together, the cells at the extremities of each were less heated than those towards the middle; the maximum of heat was at a part situated nearer to the positive pole; and the temperature gradually diminished in the direction of the negative pole.*

(31.) Ignition, in various degrees, is produced by the passage of voltaic electricity through metallic wires, when their size and length are properly proportioned to the kind of apparatus, and to the quantity of electric fluid they have to convey. Iron wire is in general easy to ignite, and is often fused into globules; and steel wire is made to burn with a rapid and brilliant combustion. A wire of platina, a metal not susceptible of being acted on by the air, may be kept at a red, or even white heat, for an indefinite length of time, by voltaic electricity. As long, indeed, as the battery retains its power, there appears to be no limit to the continual evolution of heat.

(32.) The order in which the different metals are raised to a red heat by the action of galvanism, was ascertained by Mr. Children, with the aid of a very powerful apparatus of his own construction, to be as follows, namely, platina, iron, copper, gold, zinc, silver. Between copper and gold the difference is inconsiderable; and with regard to platina and iron, their relative places in the scale seem to depend upon the temperature acquired. The relations of tin and lead to the other metals could not be ascertained in these experiments, on account of their melting before they could be raised to a red heat. A beautiful illustration of the difference existing in metals as to their capacity of ignition, is obtained by placing in the circuit a wire or chain composed of alternate portions, or links of platina and silver soldered together: it will then be found that the silver links are not sensibly heated, while all those of platina become equally and intensely ignited.

(33.) It would appear that the heat produced by the voltaic battery is more intense than can be excited by any other process. In the experiments detailed by Mr. Children,* the action of his powerful apparatus raised to a red heat, visible in full daylight, the whole of a wire of platina, one tenth of an inch in diameter, and five feet and a half in length. It also effected the fusion of a variety of substances on which the heat of the best wind-furnaces makes no impressior

(34.) When very thin metallic leaves are placed in the electric current of a powerful voltaic battery they take fire, and by continuing the action, may be made to burn with great brilliancy. In

* *Edinburgh Philosophical Journal*, xiv. 57.

* In the *Philosophical Transactions* for 1815, p. 368—370.

order to exhibit these effects, the metallic leaves should be suspended to a bent wire proceeding from one extremity of the battery, and then a broad metal plate connected with the opposite extremity should be gradually brought near to them till contact is produced. The brilliancy of the effect is heightened by covering the plate with gilt foil. Gold leaf, thus treated, burns with a vivid white light tinged with blue, and produces a dark purple or brown oxide. Silver leaf gives out a brillant emerald green light, and leaves an oxide of a dark grey colour. Copper produces a bluish white light, accompanied with red sparks; its oxide is dark brown. Tin exhibits nearly the same phenomena, excepting that its oxide is of a lighter hue. Lead burns with a beautiful purple light; and zinc with a vivid white light, inclining to blue, and fringed with red. For the distinct appearance of these colours, it is necessary that the contacts should be made with a metal, and not with charcoal; for the intense white light emitted by the latter, would overpower the peculiar colours arising from the combustion of the metal.*

(35.) A beautiful effect, noticed by Van Marum, is produced by connecting a slender iron wire with one of the poles of a powerful voltaic battery, and bringing its end in contact with the surface of some mercury connected with the other pole. Vivid combustion takes place both in the mercury and in the wire; giving rise to an abundant emission of sparks, and appearing like a star or sun dispersing thousands of rays on every side. This splendid spectacle may be prolonged at pleasure, by taking care to continue the depression of the iron wire, in proportion as the metallic particles are dispersed by the combustion.

(36.) Inflammable bodies, such as oils, alcohol, ether, and naphtha, are easily inflamed by means of galvanism, when charcoal points in the circuit of the battery are brought near each other on the surface of these fluids; and gunpowder may readily be made to explode under the same circumstances.

(37.) The difference in the operation of voltaic and ordinary electricity is very manifest in their mechanical effects. The forcible separation of the particles of bodies, and destruction of their cohesion, characterize more especially the electrical explosion, in which the fluid appears to force for itself a passage through every obstacle; while the heat which occasionally manifests itself during this sudden effect, seems as if it were merely the effect of the compression and collision of the particles which are thus forcibly impelled. But the elevation of temperature which accompanies the passage of voltaic electricity, on the contrary, appears to be its immediate and direct effect; for the mechanical texture of the substance which conveys the electricity remains unaltered. If electricity in its common form possess any power of igniting bodies, its operation is too transient and momentary to produce any extensive effect; and its tendency is rather to separate and disperse the body into minute fragments, than to unite the particles into globules by fusion. We have seen that charcoal is very readily ignited by galvanism, but it will sustain a strong discharge from an electric battery without any perceptible rise in its temperature; nor is it possible to ignite it by this means. Whether reduced to fine powder, or cut into thin plates, or made to taper to a point, it resists all attempts to raise it to a red heat, or even to impart to it any sensible warmth, though subjected to the action of the most powerful battery that has yet been tried. Even when an apparently continuous stream of electricity, obtained from a large electrical machine, was made to pass through pointed wires coated with spermaceti, no part of the spermaceti was melted.

§ 4. *Electro-Magnetic Effects of Galvanism.*

(38.) We must rank among the more remarkable of the physical effects produced by the transit of voltaic electricity through conducting bodies, the induction of magnetism in iron, and the influence exerted on bodies which possess magnetic properties. But as the study of the connections which subsist between these phenomena implies a previous knowledge of magnetism, and constitutes, indeed, a distinct branch of science, it will be proper to reserve their consideration for a future treatise. It may be as well, however, to remark in this place, that the discovery of the electro-magnetic effects of galvanism have furnished us with the most delicate tests for detecting very minute portions of voltaic electricity, so that many of the results of simple galvanic arrangements,

* Singer's *Elements of Electricity*, p. 408.

to be hereafter mentioned, have been obtained by magnetic galvanometers.

§ 5. *Chemical changes effected by Galvanism.*

(39.) In the Treatise on Electricity, some of the chemical changes which result from the operation of this agent in its ordinary form were noticed; and experiments were described in which water, and a few saline bodies were decomposed by a succession of electric discharges from a powerful machine. But the power of galvanism to effect changes in the composition of bodies subjected to its action is incomparably greater; and its application has led to a series of discoveries which constitute a new era in chemistry, and rank among the most brilliant in the annals of physical science.

(40.) The chemical agency of galvanism, unlike its power of eliciting heat, is manifested, not while it is traversing substances of great conducting powers, but, on the contrary, when it meets with impediments to its passage; and it is exerted chiefly on substances, generally fluids, which convey electricity only partially and imperfectly. That we may acquire clear ideas of the connection of the chemical phenomena relating to galvanism, it will be necessary to trace them from their origin, and attend to what takes place in the simplest galvanic circle composed of two dissimilar metals and an interposed fluid.

(41.) If a plate of zinc, and another of copper, be immersed in very dilute sulphuric acid, without touching or communicating with each other, the zinc will be acted upon by the acid; part of the water will be decomposed, its oxygen combining with the zinc and forming oxide of zinc; and its hydrogen will be disengaged in the form of gas from the surface of the zinc plate. The oxide of zinc, in proportion as it is produced, will be dissolved by the acid, thereby forming sulphate of zinc. The plate of copper, which has been immersed in the same fluid, will, during all this time, have undergone no change; the acid, in its diluted state, being incapable of acting upon it. But if, while the above process is going on, the metals be brought into contact, either directly, or by the intervention of some metallic intermedium, the following changes will ensue. In the first place, the oxidation and solution of the zinc will proceed with much greater rapidity and energy than it did before; and in the second place, it will not be accompanied by the evolution of the same quantity of hydrogen gas from the oxidating surface. There will, indeed, be a disengagement of hydrogen from the whole fluid, in quantity exactly corresponding to that of the oxygen derived from the water; but the greater part of this hydrogen will now make its appearance on the surface of the copper plate, whence it will arise in a copious stream of bubbles. But still the copper will itself remain apparently unaffected by this change in the circumstances of the experiment. In process of time, indeed, when a considerable proportion of sulphate of zinc has been dissolved in the fluid, the quantity of disengaged hydrogen is found gradually to diminish, and a thin film, composed partly of metallic zinc and partly of filaments of oxide of zinc, is deposited on the surface of the copper; as soon as this happens the galvanic action ceases.

(42.) If an acid, such as the nitric acid, capable of acting upon the copper, as well as upon the zinc, be employed instead of the sulphuric acid, similar phenomena will take place, with this additional circumstance, that the action of the acid upon the copper will cease the instant the galvanic circuit is completed; and instead of nitrous gas being formed on the surface of the copper, which happens before the circuit is formed, only bubbles of pure hydrogen will make their appearance; and the copper is protected from all further action, the zinc being, as in the former case, oxidated and dissolved with additional energy. It is on this principle that Sir H. Davy has effected the protection of the copper sheeting of ships from the corrosion of sea water, by placing in contact with it pieces of zinc or iron, on which sea water exerts a greater chemical action than on copper. See Phil. Trans. for 1824, p. 151, and 242; and for 1825, p. 328.

(43.) In compound voltaic batteries, the same chemical changes which have been just described as occurring in the simple galvanic circle, take place in each of the portions of fluid intervening in the compartments between the plates.

(44.) The chemical agency of galvanism is exerted in a no less remarkable manner on fluid conductors placed in the circuit between the poles of the battery. Among the simplest of its effects is the resolution of water into its two gaseous

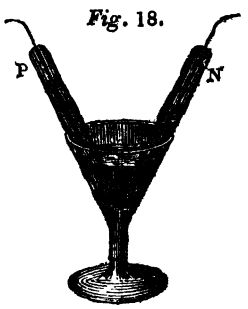
elements, oxygen and hydrogen. The discovery of this fact is due to the united researches of the late Mr. Nicholson and of Mr. (now Sir Anthony) Carlisle, and was one of the immediate consequences of the invention of the pile by Volta.

(45.) The most convenient mode of exhibiting the decomposition of water by galvanism is to fill with water a glass tube, (see *fig.* 17.) to each end of which

Fig. 17.

a cork has been fitted so as to confine the water, and to introduce into the tube two metallic wires, by passing one at each end through the cork which closes it, allowing the extremities of the wires, that are in the water, to come so near each other as to be separated by an interval of only a quarter of an inch. The wires being then respectively made to communicate with each of the two poles of a voltaic battery, the following phenomena will ensue. If the wire connected with the positive pole of the battery consists of an oxidable metal, it is rapidly oxidated by the water surrounding it—while at the same time a stream of minute bubbles of hydrogen gas arises from the surface of the other wire, which is in connection with the negative pole. But if we employ wires made of a metal which is not susceptible of oxidation by water, such as gold or platina, gas will be extricated from both the wires, and by means of a proper apparatus may be collected separately. This may be accomplished by taking two glass tubes, or receivers, closed at one end, and filled with water; this fluid is retained by inverting them over a sufficient quantity of water contained in a glass vessel, as is shown in *fig.* 18. Each tube is to be

Fig. 18.



furnished with a platina wire, P and N, passed through the closed extremity, and descending within it through its whole length. The open ends are then to be placed as near to each other as their position in the water will allow; and the wires are to be connected respectively with the opposite poles of a voltaic battery. Gas will immediately be seen to rise from each of the wires, but in different quantities. The tube containing the negative wire, N, will be soon filled with hydrogen gas, while the other, which is traversed by the positive wire, P, will, in an equal time, be only half filled with oxygen gas. This arises from the circumstance that the volumes of the two gases, which form water when combined, or which are the products of the decomposition of water, are in the above proportion; that is, the volume of the hydrogen is to that of the oxygen gas as two to one. That the water is in this experiment perfectly resolved into its two elements is satisfactorily proved by mixing together the gases thus obtained, and firing the mixture by the electric spark; when the whole instantly loses its gaseous form, and is reconverted into water.

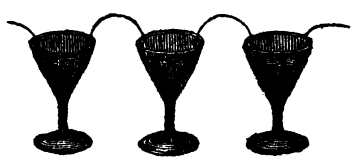
(46.) If the water employed in the preceding experiment be not perfectly pure, other substances besides oxygen and hydrogen will also make their appearance at the two wires, and the apparent formation of such substances from water was the occasion of great perplexity to the earlier experimentalists. But Sir H. Davy succeeded in proving, by a most masterly train of investigation, that when every precaution is taken to ensure the purity of the water subjected to the operation of galvanism, the only products obtained are the two gaseous elements of water, oxygen, and hydrogen

(47.) In these experiments it became manifest, that under the influence of voltaic electricity neutral salts, existing in any solution, were decomposed, the acid portion being accumulated around the positive wire, on the same points where the extrication of oxygen took place; while the bases, whether earthy, alkaline, or metallic, were, at the same moment, transferred along with the hydrogen to the negative wire. The best mode of exhibiting these decompositions, is to employ two cups, made either of glass, or, where great precision is requisite, of agate, or of gold; the liquids contained in these cups being connected together by a few fibres of moistened asbestos,

and subjected to the action of the voltaic battery. If the liquid contain any soluble saline compound, such as sulphate of soda, or common Glauber's salt, and the operation be continued a sufficient time, the whole of the acid contained in the salt will be found collected in the positive cup, and the whole of the alkali in the negative cup. Nor is any considerable solubility in the body placed in the circuit necessary for its decomposition by galvanism. Two cups made of compact sulphate of lime, containing pure water, were connected together by fibrous sulphate of lime, moistened by pure water, and the voltaic current transmitted through them. After an hour the fluids were accurately examined, when it was found that the negative cup contained a pure and saturated solution of lime, partially covered with a calcareous crust; while the positive cup was filled with a moderately strong solution of sulphuric acid. Sulphate of strontites, and fluate of lime, subjected to the same process, yielded similar results: sulphate of barytes, from its greater insolubility, proved more difficult of decomposition; but the difficulty was at length overcome. The analysis of many mineralogical specimens, of which the composition was much more complicated, was greatly elucidated by the application of voltaic electricity, which effected the extraction of all the acid and alkaline matters they contained.

(48.) For the production of these effects it is immaterial in what part of the fluid line of circuit the decomposable body happens to be situated. This will appear by placing three cups, side by side, in a line (*fig.* 19.), and connecting

Fig. 19.



them together by moistened asbestos. Let a solution of sulphate of potash, or any other neutral salt, be put into the middle cup, and blue infusion of cabbage into the other cups. When these fluids are placed in the circuit of the voltaic battery, by immersing the wires into the fluid in the outer cups, the sulphuric, or other acid, will collect in the positive cup, and render its blue infusion red, while the alkali will pass into the opposite cup, and tinge its blue contents green.

(49.) When metallic solutions are subjected to the decomposing action of galvanism, a deposition of the metal, generally in the form of minute crystals, takes place on the negative wire, and oxide is also deposited around it; while the acid passes over, as before, into the positive cup. This effect takes place with solutions of iron, zinc, and tin, as well as with the more oxidable metals.

(50.) When a solution of nitrate of silver has been placed on the positive side, and distilled water on the negative, the whole of the connecting asbestos becomes covered with a thin metallic film of silver. We have been the more particular in noticing these effects, because, as was before observed (§ 41.), they occur to a greater or less extent in the fluids which occupy the cells of the battery, and have a considerable influence in modifying, and ultimately destroying the power of the instrument.

(51.) Phenomena of a still more extraordinary nature, presented themselves to Sir H. Davy in the further prosecution of these inquiries. It was discovered that the elements of compound bodies were actually conveyed by the influence of the electric current through solutions of substances, on which, under other circumstances, they would have exerted an immediate and powerful chemical action, without any such effect being produced. Acids, for example, may be transmitted from one cup, connected with the negative pole, to another cup on the opposite or positive side, through a portion of fluid in an intermediate cup tinged with any of the vegetable coloured infusions, which are instantly reddened by the presence of an acid, without occasioning the slightest change of colour. The same happens also with alkalies. If three cups be arranged as before, (see *fig.* 19.) and connected with each other in a series by moistened cotton, the middle cup, and also the one next to the positive side of the battery, being filled with blue infusion of cabbage, or of litmus; and the cup next to the negative side containing a solution of sulphate of soda; on the series being placed in the voltaic circuit, a red tinge will soon be perceived in the water of the positive cup, which will become strongly acid. It is evident that the sulphuric acid so trans-

ferred must have passed through the fluid in the middle vessel, but without affecting the coloured solution in its passage. By reversing the connections with the poles of the battery, a similar transfer of the alkali will be made; it will be collected in the tinged water of the negative cup, which it will render green; but the intermediate portion of fluid will not, either in this or in the former case, exhibit any trace of the substance which is carried through it by the influence of electricity.

(52.) No union, under similar circumstances, is found to take place, between acids and alkalies, when either of these active chemical principles is transmitted by voltaic electricity through the other, provided the compouud which they would form by their union remains soluble; for should the compound be insoluble, the union takes place, and the product, on falling to the bottom of the fluid by its superior gravity, is removed from the line of the electric action. When, for example, sulphuric acid is attempted to be passed through a solution of barytes, or *vice versâ*, barytes through a solution of sulphuric acid, sulphate of barytes is formed, which being insoluble in the fluid, falls down as a precipitate, and being removed from the action of the electric current, proceeds no further in its course. If some basis of mechanical support be provided, whereby this removal from the voltaic influence can be prevented, the transfer may sometimes be continued, notwithstanding the body has assumed a solid form; thus magnesia or lime will pass along moist asbestos, from the positive to the negative sides; but if a vessel of pure water be interposed, they do not reach the negative vessel, but sink to the bottom. In like manner when nitrate of silver was on the positive side, and distilled water on the negative, the silver, as we have already seen, passed along the transmitting fibres of the asbestos, so as to cover it with a thin metallic film.

(53.) When the fluids placed in the same voltaic circuit are connected, not by fluids, but by pieces of metal, such as wires, the changes above described take place in each separate portion of fluid, each alternate metallic surface performing the functions of a positive and negative polarity, according to its place in the circuit of the electric current. Those parts into which the electricity is entering possess properties corresponding to those of the negative wires or poles of the battery; and those which are giving exit to the electricity, act as positive wires. The former will collect around them the several bases of neutral and metallic salts, and the hydrogen of the decomposed water; the latter will collect oxygen, and the compounds in which oxygen predominates, such as the acids.

(54.) The decomposition of the alkalies and of the earths, which crowned this brilliant career of discovery, is, in point of theory, only a particular instance of the general fact above stated, namely, that combustible substances are carried to the negative wire, and oxygen evolved at the positive wire. Various other applications have been made of the voltaic battery to the purposes of chemical decomposition. Sulphuric acid is resolved by its means into oxygen gas and sulphur. Phosphoric acid, in like manner, yields oxygen gas and phosphorus. Ammonia separates into hydrogen and azote, with a small proportion of oxygen. Oils, alcohol, and ether, when acted on by a powerful battery, deposit charcoal, and give off hydrogen, or carburetted hydrogen. But it would be encroaching too far on the province of chemistry to extend our illustrations of this subject to any greater length.

§ 6. *Physiological effects of Galvanism*

(55.) The action of voltaic, as well as of common electricity, on a living animal is chiefly exerted on the functions of the nervous system. It is shown in the production of sensation, in the excitation of muscular contraction, and in altering the products of secretion.

(56.) If any considerable part of the human body form part of the circuit of a voltaic pile or battery, a separate shock is experienced every time a connection is made with the poles of the apparatus; provided the skin through which the electric current is to pass be sufficiently moist to allow of its being transmitted: for in its usual dry state the cuticle, or outer skin, is scarcely pervious to electricity of such low intensity as that afforded by galvanism. The most effectual method of receiving the whole force of the battery is to wet both hands with water, or what answers still better, with a solution of common salt, and to grasp a silver spoon in each; the circuit is then to be completed by touching one pole of the battery with one spoon, and the opposite pole with the other spoon. Another mode is to plunge

a finger of each hand into two separate vessels filled with water, into which the extremities of the two wires from the battery have been immersed. The shock received from the voltaic pile is similar to that resulting from a large electrical battery very weakly charged: and its intensity is greater in proportion to the number of series of elements composing the pile. Twenty pair of plates are generally sufficient to give a shock, which is sometimes felt in the arms: with a hundred pair it extends to the shoulders.

(57.) Independently of the shock felt on the first impression of voltaic electricity communicated from the battery, the continued flow of the current through the body, as long as it forms part of the circuit, is generally accompanied by a continued aching pain. If it pass through any external part deprived of cuticle, it produces a severe smarting or burning sensation, which, if the exposed surface be large, continues to increase till it is scarcely supportable. This painful feeling is experienced if the slightest cut, burn, or excoriation of any kind, happen to be in the path of the electrical current: and it will be excited in these parts, even by a single pair of plates, forming a galvanic combination. It has been remarked by Volta that the pain is of a sharper kind on those sensible parts of the body, included in the circuit, which are on the negative side of the pile; that is, where the electricity flows out from the body, than where it enters: a fact which has also been noticed with regard to the pungency of the common electrical spark.*

(58.) The impression made by voltaic electricity on some of the nerves of the face, when they form part of the circuit, is accompanied by the sensation of a vivid flash of light. The simple application of a piece of zinc and one of silver to the tongue or lips, frequently gives rise, at the moment of the contact of the metals, to this perception of a luminous flash: but the most certain way of obtaining this result is to press a piece of silver as high as possible between the upper lip and the gums, or to insert a silver probe into the nostrils; while, at the same time, a piece of zinc is laid upon the tongue; and then to bring the two metals into contact. Another mode is to introduce some tinfoil within the eyelid, so as to cover part of the globe of the eye, and place a silver spoon in the mouth, which must then be made to communicate with the tinfoil by a wire of sufficient length; or conversely, the tinfoil may be placed upon the tongue, and the rounded end of a silver probe applied to the inner corner of the eye; and the contact established as before. The flash which results from the action of a pile, applied in this way, is very powerful; and if the plates were numerous, the experiment might occasion permanent injury to the sight This phenomenon is evidently produced by an impression communicated to the retina, or optic nerve, and is analogous to the effect of a blow on the eye, which is well known to occasion the sensation of a bright luminous coruscation, totally independent of the actual presence of light. In like manner the flash from galvanism is felt whether the eyes be open or closed, or whether the experiment be made in day-light or in the dark. If the pupil of the eye be watched by another person when this effect is produced, it will be seen to contract at the moment when the metals are brought into contact. A flash is also perceived at the moment the metals are separated from each other.

(59.) The peculiar taste which is perceived when different metals are applied to different parts of the tongue, and made to touch each other, has already been noticed. It is essential to the success of the experiment, that the surface of the tongue should be moist; for when the tongue is previously wiped very dry, the effect is considerably diminished, and it is not at all perceptible, if the surface is absolutely dry. The quality of the metal laid upon the tongue influences the kind of taste which is communicated; the more oxidable metal giving rise to an acid, and the less oxidable metal to an austere or alkaline taste. Similar differences have been observed by Berzelius, with regard to the sensations excited in the tongue by common electricity, directed in a stream upon that organ, from a pointed conductor; the taste of positive electricity being acid, and that of negative electricity caustic and alkaline. This circumstance would tend to prove that the taste perceived in the galvanic experiment is owing to the actual presence of acids and alkalies, derived from the chemical decomposition of the salts contained in the saliva, by the galvanic

* Nicholson's *Journal*, 4to. iv. 180.

action; and that it is not merely the effect of a direct impression of the electric current on the nerves of the tongue.

(60.) When the current of voltaic electricity is made to pass along a nerve distributed to any of the muscles of voluntary motion, these muscles are thrown into violent contractions of a convulsive kind. It was an observation of this kind that led the way, as we have already seen, to the discovery of the galvanic influence. The muscles of a frog are, indeed, peculiarly sensible to this influence, and are therefore the fittest for the exhibition of this phenomenon, with very weak galvanic powers. The susceptibility of some of the animals belonging to the class of *vermes*, is also very great. If a crown piece be laid upon a plate of zinc of larger size, and a living leech be placed upon the silver coin, it will suffer no inconvenience as long as it remains in contact with the silver only; but the moment it has stretched out its head so as to touch the zinc, it suddenly recoils, as if it had experienced a painful shock. An earthworm will also exhibit the same kind of sensitiveness; and the same effect is still more strikingly exhibited by the *nais*, which is an aquatic worm. Humboldt found that the *lernæa*, or water-serpent, and even the *tænia*, *ascaris*, and other species of intestinal worms, had their movements accelerated by the influence of galvanism, which also speedily destroyed their life. Powerful shocks from a voltaic battery are no less immediately fatal to animals, than discharges from an ordinary electric battery.* Small animals are easily killed by discharges which would only produce a temporary stunning effect on larger animals.

(61.) Convulsive movements may be excited by galvanism in the muscles of an animal, after its death, as long as they retain their contractility. These effects become exceedingly striking, when large animals are made the subjects of experiment, and when powerful batteries are employed. Thus if two wires, connected with the poles of a battery of a hundred plates, be inserted into the ears of an ox, or sheep, when the head is removed from the body of the animal recently killed, very strong actions will be excited in the muscles of the face every time the circuit is completed. The convulsions are so general, as often to impress the spectator with a belief that the animal has been restored to the power of sensation, and that he is enduring the most cruel sufferings. The eyes are seen to open and shut spontaneously, they roll in the sockets as if again endued with vision; the pupils are at the same time widely dilated. The nostrils vibrate as in the act of smelling; and the movements of mastication are imitated by the jaws. The struggles of the limbs of a horse galvanised, soon after it has been killed, are so powerful as to require the strength of several persons to restrain them.

(62.) It is needless to enter into the details of experiments of a similar kind performed in hospitals on limbs removed by amputation; or on the bodies of criminals soon after their execution. A great number of these are stated to have been made at Turin, on the victims of the guillotine; and in this country, Aldini, by operating with a considerable number of plates on the body of a criminal executed at Newgate, produced effects very similar to those already described in the sheep and ox; but which were necessarily of a more impressive character, from their conveying the more terrific expressions of human passion and of human agony.

(63.) Muscles whose actions, like those of the heart, are not under the guidance of the will, are less easily affected by galvanism than the muscles of voluntary motion. But Fowler, Vassali, Humboldt, Nysten, and others, have sufficiently proved that even these muscles may, by the proper application of this power, be made to contract.

(64.) The most curious and hitherto unexplained of the physiological effects of galvanism, are those on the functions of secretion, especially on that of the gastric juice, a fluid which is essentially subservient to the process of digestion. But these topics appertain more to physiology than to the subject of the present treatise.

Chapter V.

Theory of Galvanism

(65.) The various attempts which have at different times been made to explain the phenomena of galvanism, by the application of the laws which are known to govern those of ordinary electricity, have on the whole been attended with very indifferent success; and the theory

* See Treatise on Electricity. § 192.

of this science remains, even at the present day, involved in considerable uncertainty and obscurity. No very distinct or satisfactory account has yet been given of the nature of that force, which originally disturbs the electrical condition of the different parts of the voltaic apparatus, and constitutes the primary source of galvanic power. It was long the prevailing hypothesis, that this force was the same with that which gives rise to the developement of electricity during the contact of dissimilar metals; a fact, the principal circumstances attending which have been stated in the treatise on Electricity. (§ 203.) But in proportion as a more extensive acquaintance with the phenomena afforded the means of a more accurate analysis, the insufficiency of this, which was termed the *Electrical Theory*, became more apparent; and it is now fully established, that the primary agent in the evolution of electricity, is the force of chemical attraction. This latter view of the subject, has led to what may be called the *Chemical Theory of Galvanism.*

(66.) Every scientific theory must have for its basis some general fact, comprehending a multitude of subordinate phenomena, which are its more or less direct consequences. The chemical theory of galvanism assumes the following as the most general fact in that science: namely, that chemical action, occurring between a fluid and a solid body, is always accompanied by the disturbance of electric equilibrium; in consequence of which a certain quantity of electricity is developed, or, in other words, converted from a latent into an active state. So intimate, indeed, is the connection between the electrical and the chemical changes, that the chemical action can proceed only to a certain extent, unless the electrical equilibrium which has been disturbed be again restored. The oxidation of metallic bodies (that is, their combination with oxygen) is more especially accompanied by the developement of large quantities of electricity. Thus it has been ascertained, that when a plate of zinc is chemically acted upon by dilute sulphuric acid, which produces first oxide, and then sulphate of zinc, the metal becomes negatively electrified, while the liquid is in the same degree positively electrified. This fact, when stated conformably to the hypothesis of Franklin, implies the abstraction of the electric fluid from the zinc, and its transference to the liquid product of the combination: but, when translated into the language of the hypothesis of a double fluid, must be understood as the separation of the two electricities by the chemical action, and the determination of the resinous or negative electricity in the direction of the zinc, and of the vitreous or positive electricity in the direction of the oxidating liquid. In order to avoid perplexity, however, we shall continue to adhere to the simpler of these hypotheses; and advert only to the conditions and movements of positive electricity. (§ 4.)

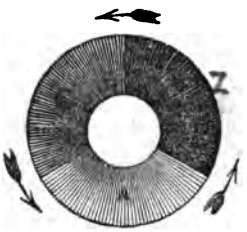
(67.) That two conducting bodies, such as zinc and acid, thus remain, the one in a negative, and the other in a positive electrical state, notwithstanding their being in contact, is known to us as a matter of fact; but it is a fact which is not explicable by any of the laws of ordinary electrical phenomena, or, in other words, it is not reducible to any other more general fact. We must for the present, therefore, be content to leave it as a subject of future inquiry, to determine to what peculiarity in the circumstances attending the changes of chemical composition it is owing, that the electric equilibrium is permanently disturbed, and what is the unknown obstacle that prevents its restoration. A similar difficulty occurring in the case of the electricity produced by contact, has been noticed in the treatise on Electricity. (§ 204.)

(68.) As long as the chemical action proceeds, the transfer of electricity from the metal to the fluid continues; but the rapidity of the process is checked by the circumstance, that as soon as the quantity transferred has accumulated so as to reach a certain degree of intensity, which is generally exceedingly low, all action ceases, the chemical affinities being balanced by an opposing electrical force. But in consequence of the gradual absorption of electricity by the metal from surrounding bodies, and the gradual dissipation of the superabundant electricity of the fluid, this state is never reached; or, if attained, does not long subsist: and the chemical affinities continue to produce their effects, though more slowly than if their operation were uncontrouled by the electrical force. But if, on the other hand, by the interposition of good conductors, a ready passage be afforded for the electricity from the fluid, where it is accu-

mulated, to the metal where it is deficient, then the obstacle to the further exertion of the chemical affinities between these two bodies will be removed, and the action will now proceed with much greater energy. This is precisely what is accomplished by galvanic combinations. Some metal, such as copper, silver, gold, or platina, not susceptible of oxidation by the fluid employed, is applied to this fluid, collects from it the redundant electricity, and then being brought into contact with the zinc, or metal acted upon by the fluid, communicates to it this electricity, and thus continually restores the electric equilibrium, the very instant after it has been disturbed. We find, accordingly, that under these circumstances, that is, whenever the galvanic circuit is completed, the oxidation of the zinc proceeds with renewed activity; but ceases, or at least takes place more slowly, whenever this circuit is interrupted.

(69.) In order to take a more comprehensive view of the subject, we may state the following as the conditions that are essential to galvanic action. First, the presence of three elements is required, which we shall designate by the letters A, Z, and C. Between the two first of these, A and Z, some chemical affinity must exist, adequate to produce combination and developement of electricity; while the same action, or at least the same degree of that action, is not exerted between the third element C, and either of the former. Secondly, it is necessary that one of the two first bodies, which we shall suppose to be Z, be a solid,* and that it possess a high degree of conducting power with regard to electricity. As it is a general law in chemistry that no chemical action can take place between two bodies, unless one of these bodies be in a fluid state, it follows that as Z is a solid, so A must be a fluid body; on the other hand, the body C may be either solid or fluid. Thirdly, it is requisite that all the three bodies be in mutual contact, so as to compose a kind of circular arrangement, as is represented in *fig* 20. If all these conditions be fulfilled, it is found that a continued stream or current of electricity will circulate in a determinate direction through the bodies thus placed, as long as the chemical action continues. If the bodies Z, A, and C, be respectively zinc, acid, and copper, the surface of contact between Z and A will be that at which the chemical action and consequent developement of electricity takes place; for C may be considered as acting merely the part of a conductor of that electricity between A and Z; and the current will circulate in the direction denoted in the figure by the arrows, that is, from A to C, and thence to Z.

Fig. 20.



(70.) The absolute quantity of electricity which is thus developed, and made to circulate, will depend upon a variety of circumstances, such as the extent of the surfaces in chemical action, the facilities afforded to its transmission, &c., —causes the operation of which we shall afterwards have occasion to examine. But its degree of intensity, or *tension* as it is often termed, will be regulated by other causes, and more especially by the energy of the chemical action. In a single galvanic circle, however, it is necessarily very low, being limited by the nature of the process to which it owes its origin, and to which it is in some respects opposed. It may be much increased, however, by combining together the power of a number of circles, as is done in the pile and voltaic battery. Taking the common trough battery as an example, and tracing the several steps of the process, we shall find that the electricity which the liquid in the first cell has acquired from the first plate of zinc exposed to its action, is taken up by the copper plate belonging to the second pair, and transferred to the second zinc plate, with which it is connected. This second plate of zinc, having thus acquired a larger portion of electricity than its natural share, is capable of supporting a more intense chemical action than it would otherwise have done; and hence it communicates a larger quantity of electricity to the fluid in the second cell. This increased quantity is

* Sir H. Davy has shown that chemical action taking place between two fluids, although intense, is not attended with the disturbance of the electric equilibrium. *Philosophical Transactions* for 1826, p. 399, 400.

again transmitted to the next pair of plates, and renders the third zinc plate capable of maintaining a still more powerful chemical action than the preceding plate; and thus every succeeding alternation is productive of a further increase, both in the quantity and intensity of the electricity developed.

(71.) The simplest cases are those in which no chemical action whatever is exerted either between the fluid A and the body C, or between C and Z; and the force of the electric current will then be proportional simply to the energy of the chemical action taking place between A and Z. But either A and C, or C and Z, may also have some chemical action on one another; and it will depend on the nature of that action whether the electric force to which it gives rise opposes or concurs with the force resulting from the action between A and Z. If the two actions be of the same kind, as, for example, if they should both be oxidating actions, the electric forces resulting from them will be in opposition to each other; for while the one is impelling the current from Z to A, the others will tend to impel it from C to A, or from Z to C, that is, in a contrary direction. The effective electromotive force will, in all these cases, be equal to the difference between the two that are thus opposed to each other. On the other hand, if the chemical actions between A and C, or between Z and C, should happen to be of an opposite kind, with regard to their electrical tendencies, to that between Z and A, they will communicate to the developed electricity an impulse in the same direction, and the resulting electromotive force will be equal to the sum of the conspiring forces.

(72.) We have seen that the third element C may be either a solid or a fluid body, and we may therefore distinguish galvanic circles into two kinds, according as C has the one or the other of these two forms. In the first, the circle is composed of two solids and one fluid; in the second, of one solid and two fluids. Of the solid elements capable of forming galvanic combinations, the most efficacious are the metals, and charcoal. Of fluid elements, those which exert a powerful chemical action upon the former, such as the mineral acids, alkaline solutions, sulphurets, solutions of neutral salts, and water containing oxygen gas, or atmospheric air. The energy of the galvanic power will depend altogether upon that of the chemical action, and can never be excited when the latter condition is wanting. Thus silver and gold evolve no galvanic influence when in contact with pure water, which is incapable of acting chemically upon either of these metals; but the addition of nitric acid, or any other fluid decomposable by silver, to the water, immediately renders this combination of elements an active galvanic circle.

(73.) With regard to the direction given to the electrical current by the chemical action of two bodies, we may lay it down as a general rule, to which there are but few exceptions, that the electricity is determined from the solid to the fluid which acts upon it chemically. This we have already seen exemplified in the instance so frequently referred to of the ternary arrangement of zinc, acid, and copper. Another, and very common mode of expressing the same fact is, to say that the zinc is rendered positive with regard to the copper, and, *vice versâ*, the copper negative with reference to the zinc. In this sense, that is with relation to the action of acids and other oxidating fluids, every oxidable metal is positive with regard to a metal which is oxidable in a less degree.

In order to determine beforehand the effect of any combination of two metals in a galvanic circle with any of the acids, it will be convenient, therefore, to arrange the metals in the order of their oxidability. With this view the following catalogue has been given by Sir Humphry Davy:* viz.

Potassium and its amalgams.
Barium and its amalgams.
Amalgam of zinc.
Zinc.
Cadmium.
Tin.
Iron.
Bismuth.
Antimony (?).
Lead.
Copper.
Silver.
Palladium.
Tellurium.
Gold.
Charcoal.
Platina.
Iridium.
Rhodium.

(74.) In a ternary galvanic arrangement with acids, then, each metal in the above list is positive to all those which

* *Philosophical Transactions* for 1826, p. 406.

follow it; and the more so in proportion as the two metals are more distant from each other in the scale. Thus zinc and iron will compose a weaker circle than zinc and silver; and zinc and platina will form one of still greater power. It may be observed, however, that the precise order in which the metals stand in such a scale as the above, must be understood as only strictly true with relation to the particular acid employed, and even to the particular degree of dilution that has been given to the acid. For we find slight variations in the order of relation of the metals with different acids, or even with the same acid in different states of concentration.

(75.) When alkaline solutions are employed as the fluid agent, instead of acids, the same general order is observed in the metals, with regard to their mutual electrical relations. The principal exception is with regard to iron, which is here found to occupy a place intermediate between copper and silver. Thus a combination of iron and copper will, by immersion in an acid, form a circle in which the electricity will be determined from the iron to the acid, thence to the copper, and thence to the iron; that is to say, the iron will be positive with regard to the copper. But if the same combination of iron and copper be acted upon by an alkaline solution,* and more especially by ammonia, the iron is negative with regard to the copper; for here the chemical action of the fluid upon the copper is stronger than upon the iron, and the electricity is therefore determined to the fluid from the copper, and not from the iron as in the former case. The same results are obtained when tin is employed in conjunction with copper, and with ammonia.†

(76.) With solutions of hydro-sulphurets, the several metals stand also nearly in the same order, as to their electrical relations, as with acids—with a few exceptions, however, as will appear from the following catalogue, given by Sir H. Davy:—

Zinc.
Tin.
Copper.
Iron.
Bismuth.
Silver.
Platina.
Palladium.
Gold.
Charcoal.

We may observe, that here also copper is positive with regard to iron; so that when these two metals form a circle with a solution of hydro-sulphuret, the electrical current is in an opposite direction to what it is when the same combination of metals is plunged in acids.

(77.) It need hardly be observed, that every thing that has been stated with regard to single galvanic circles applies also to compound circles, whether in the form of the pile, or the trough battery, composed of the same elementary parts.

(78.) We have next to consider the second class of galvanic circles; those, namely, which are composed of a single solid and two fluid elements.

The arrangement assumed in this case by the three elements of the circle, may be represented by the same diagram as before, *fig.* 20. Z will then denote the solid; A the acting fluid, and C the conducting fluid. As there is a necessity for separating the two fluids, they may be contained in separate vessels, and be made to communicate by means of a bent tube, inverted like a syphon, full of some conducting liquid, and passing over from the one to the other of the two fluids. Sir H. Davy uses, in many of his experiments, fibres of moistened asbestos in place of the tube, for establishing a communication between the fluids. Two plates of the same metal are then to be immersed in the fluids, and made to communicate by wires, or slips of the same metal.

(79.) Sir H. Davy has distinguished three different kinds of circles of the second class.*

The first and most feeble is composed of single metallic plates, arranged in such a manner, that two of their surfaces are in contact with different fluids, one capable, and the other incapable, of oxidating the metal. Zinc, acid, and water, occupying the situations of Z, A, and C, in the diagram, may be taken as an example; and it will be seen that the only difference between this arrangement and those of the former class, consists in the substitution in the circle of water for copper; but the function of each of these parts is essentially the same, namely, that of simply conducting electricity between the other

* Davy, *Elements of Chemical Philosophy*, p. 148.
† De la Rive, *Annales de Chimie*, xxxvii, 232.

* *Philosophical Transactions* for 1801, p. 398.

two elements. As the conducting power of fluids, however, is much inferior to that of metals, the electrical indications will be more feeble than in circles of the first class; and, indeed, will scarcely be sensible unless we employ the more easily oxidable metals, such as tin and zinc. But powerful effects may be obtained by combining a number of such circles in a pile or battery. For constructing an instrument of the former kind, Sir H. Davy directs pieces of polished tin, about an inch square and one-twentieth of an inch thick, to be piled up with woollen cloths of the same size, moistened some in water, and some in dilute nitric acid, in the following order,—tin, acid, water, and so on. It is proper to observe the precaution of placing the cloth moistened with acid underneath the one which is moistened with water; for, as the acid is specifically heavier than the water, little or no mixture of fluid will then take place. Twenty such alternations will produce a battery capable of acting weakly on the organs of sense, and of slowly decomposing water. When zinc is the metal used, it is necessary, on account of its rapid oxidation in water containing atmospheric air, to use three cloths; the first moistened with a weak solution of hydro-sulphuret of potash, which has no power of acting upon zinc, and which prevents it from being acted upon by the water; the second moistened with a solution of sulphate of potash, of greater specific gravity than the solution of hydro-sulphuret; and the third wetted with an oxidating fluid, such as an acid, specifically heavier than either of the solutions. In this case, if, proceeding upwards, the order be as follows — zinc, — oxidating solution,—solution of sulphate of potash,—solution of hydro-sulphuret of potash, very little mixture of the fluids, or chemical action between them will take place; and an alternation of twelve series of this kind, forms a battery capable of producing sensible galvanic effects. The direction of the electrical current is, as usual, from the zinc to the oxidating fluid.

(80.) It has often been remarked that porter drank out of a pewter pot has a brisker taste than when taken out of a glass. Professor Robison ascribed this to the influence of galvanism, arising from the circle formed by the metal and two different fluids. He considered that in the act of drinking, one side of the pewter pot is exposed to the action of the saliva which moistens the lip, while the other side of the metal is touched by the porter; the circle being completed when the latter fluid comes in contact with the tongue.

(81.) The second kind of galvanic combinations with a single metal, consists of a series of plates composed of a metal capable of being acted upon by sulphuretted hydrogen, in contact with solutions of hydrosulphurets on the one side, and water on the other, placed in a regular order of alternation. Under these circumstances, a current of electricity is produced, the direction of which is the reverse of what it is in the former case, the surface of the metallic plate in contact with the solution of sulphur being positive, while that in contact with acid is negative. Eight series will produce sensible effects. Copper, silver, and lead are each capable of forming this combination; their comparative activity being in the order in which they are here enumerated, that is, copper the most, and lead the least.*

(82.) A familiar instance of the operation of galvanism in promoting the combination of sulphur with silver, occurs in the employment of a silver spoon in eating the yolk of an egg; a galvanic circle of the second kind being formed by the yolk, which contains sulphur, the silver spoon, and the saliva of the tongue.

(83.) The third kind of combinations unite the power of the two former, and consist of a single metal, acted upon on one side by an acid, and on the other side by the hydro-sulphurets. Copper, silver, or lead may here be employed, and the order of their powers is the same as in the preceding instance. The pile may be constructed in the same manner as the pile with zinc in the first kind of combination; the cloths moistened with acid being separated from those moistened with solution of hydro-sulphuret by an intermediate cloth soaked in solution of sulphate of potash. Three plates of copper, or silver, arranged in this manner, in proper order, produce sensible effects; and a pile composed of twelve or thirteen series is capable of giving weak shocks and of rapidly decomposing water. The current of electricity is determined as in the two former cases.

(84.) Greater permanency may be

* *Philosophical Transactions* for 1801, p. 400.

given to the effects of these combinations of a single metal with two fluids, by a disposition of the plates similar to the trough of Cruickshanks, with partitions alternately of metal and of horn or glass; and with the cells filled alternately with the different solutions, according to the kind of combination employed; these fluids being connected in pairs with each other, by slips of moistened cloth, carried over the non-conducting plates.

(85.) Efficient galvanic circles may also be formed with a single metal and with the same fluid solvent, (an acid, for example,) provided the action of the latter is different on the two sides of the metal, by being of different degrees of strength. Thus, if one of the branches of a tube, bent in the form of a V, contain concentrated sulphuric acid, while the same acid in a diluted state occupies the other branch, in which case the two fluids will, on account of the difference in their specific gravities, remain without mixing with each other; and two portions of the same metal, zinc for instance, be then immersed in these fluids, and made to communicate with each other, galvanic electricity will be evolved, and determined from the metal to the diluted acid, in consequence of the action of this portion of acid upon the zinc being greater than that of the concentrated acid. But with those metals, which are more acted upon by the latter than by the former, the influence of the concentrated acid will preponderate, and the current will be determined in an opposite direction. In like manner it has been observed, that two solutions of common salt, the one concentrated, the other diluted, form a galvanic circle with copper; that metal being more acted upon by the latter than by the former, became negative to the one and positive to the other.*

(86.) The application of these principles will explain a variety of apparently anomalous facts, which are continually presenting themselves in the course of experimental researches. Sir H. Davy observed, for instance, that when two pieces of the same polished copper were introduced at the same moment into the same solution of hydro-sulphuret of potash, there was, as might be expected, no action; but if they were introduced in succession, there was a distinct, and often, if the interval of time was considerable, a violent electrical effect; the piece of metal first plunged in being negative with relation to the other. This is owing to the rapid formation at the surface of contact of sulphuret of copper, which, by its presence, prevents, or at least diminishes, the further action of the fluid; the clean surface of the plate last introduced is therefore attacked comparatively with greater force, and determines a galvanic effect.* Many singular and apparently capricious changes of electric states occur in these and other experiments of the same kind, whenever new substances are produced by the chemical action, which at first adhere to the metal, but are liable to be detached in smaller or larger portions, and thus occasion sudden alterations in the conditions of the galvanic elements.

(87.) Having thus seen how, under certain circumstances, it is possible to form various galvanic combinations with a single metal and a single fluid, it remains for us to notice the attempts that have been made to produce the same effect without the aid of any metallic substance, or even of charcoal. Lagrave announced that by placing upon each other alternate layers of muscle and of brain, from a human body, with pieces of moistened cloth or leather interposed, he formed a pile which produced galvanic effects.† Dr. Baconio, of Milan, composed a galvanic pile entirely of vegetable substances: namely, discs of red beet-root, two inches in diameter; and discs of walnut-tree, of the same size, divested of their resin by digestion in a solution of cream of tartar in vinegar. With a pile so constructed, and with a leaf of scurvy-grass as a conductor, he is said to have excited galvanic convulsions in a frog.‡ Aldini also succeeded in producing the same effect without the intervention of any metallic substance; sometimes by bringing into contact the nerve of one animal with the muscle of another, and at other times by employing the nerves and muscles of the same animal. In some of his experiments the most powerful contractions were excited, by bringing the parts of a warm-blooded animal into contact with those of a cold-blooded animal. On introducing, for

* Becquerel, *Annales de Chimie et de Physique*, xxxv. 120.

* *Philosophical Transactions* for 1826, p. 393.

† *Journal de Physique*, lvi. 235; and Nicholson's *Journal*, v. 62.

‡ Nicholson's *Journal*. xviii. 159.

example, into one of the ears of an ox recently killed a finger of one hand, moistened with a solution of salt, and holding in the other hand a prepared frog, when the spine of the frog was made to touch the tongue of the ox, convulsions took place in the limb of the frog. In like manner, when he held a prepared frog by one hand, moistened with solution of salt, and applied the crural nerves of the animal to the tip of his own tongue, convulsions were produced.* Many of these experiments were made in presence of the members of a commission of inquiry appointed by the French Institute: and they have since been repeated with success in London, at the Anatomical Theatre in Great Windmill Street.

(88.) It is well known that several fishes, such as the *torpedo*, which is a species of ray; the *gymnotus electricus*, or the electric eel; the *silurus electricus*, a species peculiar to some of the rivers in Africa; and also the *trichiurus indicus*, and *tetraodon electricus*, which are fishes found in the Indian ocean possess the power of giving electrical shocks to animals that touch them, or communicate with them by electrical conductors. Anatomical investigation has shown that this power resides in organs of a very peculiar construction. In the torpedo they are composed of a great multitude of vertical and parallel membranous plates, arranged in longitudinal columns of quadrangular, pentagonal, or hexagonal forms, with a loose net-work of tendinous fibres passing transversely and obliquely between the columns, and uniting them firmly together. Each column is, moreover, divided by a great number of thin horizontal partitions, placed over each other at very small distances, and forming numerous interstices, which appear to contain a fluid. All these parts are supplied by a great abundance of blood-vessels, and by a still more extraordinary proportion of nerves.

(89.) In the regular arrangement of their plates these organs have a marked resemblance to a voltaic battery; we know nothing, however, of the immediate source from which they derive electrical properties. Mr. Cavendish compared the action of the torpedo to that of a large electrical jar very weakly charged: and Volta considered it as still more analogous to that of the galvanic pile. Sir Humphry Davy, with a view to ascertain the justness of Volta's comparison, passed the shocks given by living torpedos through the interrupted circuit made by silver wire through water, but could not perceive that it produced the slighest decomposition of that fluid. The same shocks made to pass through a fine silver wire less than one thousandth of an inch in diameter did not produce ignition. Volta, to whom Sir H. Davy communicated the results of these experiments, considered the conditions of the organs of the torpedo to be best represented by a pile, of which the fluid substance is a very imperfect conductor, such as honey; and which, though it communicated weak shocks, yet did not decompose water. Sir H. Davy also ascertained that the electrical shocks given by the torpedo, even when powerful, produced no sensible effect on an extremely delicate magnetic electrometer. In a paper recently read at the Royal Society, he explains these negative results by supposing that the motion of the electricity in the organ of the torpedo is in no measurable time, and wants that continuity of current requisite for the production of magnetic effects.

(90.) Mr. Geoffroy St. Hilaire has found an organic structure very similar to that of the torpedo in other animals of the ray genus, which, nevertheless, do not possess any electrical powers.

(91.) Electrical effects are obtained from a pile composed of thin plates of different metals in the usual order, with discs of writing paper interposed between them. This species of pile was the invention of Mr. De Luc, who gave it the name of the *electrical column*. It may be constructed of pieces of paper, silvered on one side, by means of silver leaf, and alternated with thin leaves of zinc; taking care that the silvered surfaces of the paper discs are always in the same direction. A very large number of these may be contained in a glass tube of moderate length, previously well dried, having its ends covered with sealing-wax, and capped with brass. The most extensive instrument of this kind was made by Mr. Singer, and consisted of twenty thousand series. Each of the two ends or poles of the column affect the electrometer, and exhibit electrical attractions and repulsions; the apparatus will even give sparks, and communicate shocks of considerable force: but it possesses no sensible power of chemical decomposition when applied to fluids in the interrupted circuit. If two

* Nicholson's *Journal*, iii. 298.

upright electrical columns be placed side by side, with their poles in opposite directions, and connected at their upper ends, while a small bell is attached to the lower end of each; the whole will act as one column, and each bell will, in consequence of the electrical actions, be alternately struck by a brass ball suspended between them; and thus a continual ringing will be produced as long as the machine remains in action, which is generally for a considerable time. This action is, however, kept up solely by the presence of moisture in the paper, for it does not take place at all when the paper is perfectly dry; and although the process of oxidation is very slow, the more oxidable metal is in process of time found to be tarnished.

(92.) An apparatus somewhat analogous to that of De Luc was constructed by Hachette and Desormes with pairs of metallic plates, separated by layers of farinaceous paste, mixed with common salt. To this instrument, although it evidently owed its efficacy to the moisture of the paste, they gave the very inappropriate name of *dry pile*. It has the same properties as the electric column, except that it is unable to give a shock. A pile having nearly similar powers was also constructed by Professor Zamboni, of Verona, with discs of paper, gilt or silvered on one of their sides, while the other side was covered with a layer of pulverized black oxide of manganese, mixed with honey. Both this and the former instrument retained their power for a great length of time.

(93.) Piles formed simply of discs of copper and moistened card, placed alternately, were found by Ritter to have no power of developing electricity by their own action, but to be capable of receiving a charge by being placed in the circuit of a powerful voltaic battery, and of thus acquiring, though in an inferior degree, all the properties of the battery itself from which it derived its activity. The properties of these *secondary piles*, as they have been called, are obviously the effect of a series of electrical inductions, extending from end to end; and the apparatus is found to retain its charge for a very considerable time, provided it be kept insulated, and the communications between the two poles are not renewed too frequently.

(94.) Having thus traced the various ways in which galvanic power may be excited, we have next to examine the influence of different circumstances, by which its quantity, intensity, and mode of action are regulated. We have already seen that the intensity of the electricity developed by a single galvanic circle, bears no relation to the extent of surface of the elements which compose that circle. It follows, therefore, that however much we may increase the quantity of electricity by employing very large plates, as in the calorimotor, we cannot obtain from such an instrument any of those effects which require for their production a certain intensity, as well as quantity of electricity. In order to obtain these latter effects, we must employ the compound battery, consisting of a considerable number of alternations of the same elements. The former of these instruments, accordingly, will be capable of producing such effects as depend upon mere quantity, without regard to intensity; such as the evolution of heat, the ignition and deflagration of the metals, and electromagnetic phenomena. The compound apparatus, on the other hand, will afford the more ordinary electric appearances, (such as the spark, and the phenomena of attraction and repulsion,) will affect the electrometer, or condenser, and will communicate a charge to a Leyden jar; for in all such operations, intensity of electricity is the most essential requisite, and the power of the battery to produce them is found to be augmented by every increase in the number of the alternations. But there is also a third class of effects, more peculiarly appertaining to galvanism, which take place by the transmission of the electric current through bodies of inferior conducting power; such as liquids of various kinds, and living organized structures, both animal and vegetable: producing in the former chemical decomposition, and in the latter various physiological effects, such as nervous excitation, muscular contraction, and affections of secretion. For the production of these effects it is necessary, not only that the electricity be sufficiently powerful, both in respect to intensity and to quantity, but also that it should flow in a continuous current. It is from the difficulty of supplying this latter requisite, that the electricity derived from the common electrical machine, is, under ordinary circumstances, incapable of decomposing water in the way that is so readily accomplished by voltaic electricity. It is from deficiency of intensity, on the other hand, that we are

unable to obtain the same effects from the calorimotor, which amply fulfils the conditions of quantity and continuity. The electricity which it furnishes, however abundant in quantity, does not possess sufficient intensity to overcome the obstacle presented by the smallest thickness of water, or other liquid of low conducting power; and is, for the same reason, incapable of penetrating through the skin, or traversing through any other part of an animal body. Hence we can obtain from it neither chemical nor physiological effects. The electricity furnished by the electric column of De Luc, again, though of sufficient intensity to produce the shock and other effects of a sudden influx, is too deficient in quantity to produce chemical action; and the same general observations apply to the electricity of the torpedo.

(95.) Every circumstance that facilitates the passage of the electric current in all parts of the circuit, will tend to increase the quantity that circulates. The degree of conducting power possessed by the fluid parts of the circle, will, therefore, have an important influence on the power of the apparatus. Hence the addition of various saline bodies to the fluid is found to increase the efficacy of the voltaic battery, probably, in part at least, by increasing the conducting power of the fluid; but as such substances generally also promote chemical action, it is always in some degree doubtful what part of the effect is to be ascribed to the one or the other of these causes.

(96.) As the fluid element of the circle is the part having the smallest conducting power, the electric current will be retarded by having to pass through any considerable extent of fluid. With a view to augment the activity of the battery, it is an object to bring the two metallic surfaces of Z and C very near each other, so that the distance the electricity has to pass from the one to the other, through the fluid, shall be as small as possible; and for the same reason the surface of C, which collects the electricity from the fluid, should be sufficiently extensive to effect this purpose completely. We hence perceive the reason of the advantage derived from employing in the common trough battery, according to the suggestion of Dr. Wollaston, a double plate of copper to each plate of zinc, so that each surface of the latter metal acted upon by the fluid, may have a surface of copper opposite to it, (§ 18.); and also of enveloping each coil of zinc plate, in the calorimotor, by a coil of sheet copper, (§ 8.) Mr. Marianini has extended this principle still further, and has found that the maximum of effect takes place when the surface of the copper is no less than eight times greater than that of the zinc.

(97.) There is yet another cause of impediment to the motion of the electric current of a singular kind, and which produces very considerable effect. It appears from the experiments of Mr. Augustus De la Rive, that voltaic electricity, in passing out of one conducting body into another of a different kind, always sustains some loss of its intensity.* The amount of this loss varies much in different cases, according to the nature of the two conductors; and it is different with different degrees of intensity. In the case of the passage of the electricity from a fluid to a metal, or *vice versâ*, it is very great, and it is sensible even when it has to pass from one liquid to another, or along a mixed conductor composed of two different kinds of solids. The impediment arising from the mere change of conductor is quite independent of the peculiar conducting powers of the one or the other of the substances through which the electricity passes. Mr. De la Rive found, for example, that a much greater obstacle existed to the transmission of the electricity between sulphuric acid, especially when concentrated, and platina, than between nitric acid and the same metal; and accordingly, on sending the electric current from a voltaic battery through a number of portions of sulphuric acid, contained in separate glasses, and connected by arcs of platina wire, it proved to be a much worse conductor than when nitric acid was employed in a similar arrangement. But the conducting powers of each system of compound conductors were immediately rendered equal by dipping the ends of the platina wires in nitric acid, before immersing them in the sulphuric acid.†

(98.) In general the more readily a metal is acted upon by liquid conductors, the less is the diminution of intensity which is sustained by the passage of electric currents through them. Mr. De la Rive states it to be a general

* *Annales de Chimie et de Physique*, xxxii. 267.
† Ibid. p. 273.

law, that, independently of the effects of chemical action, the influence of the obstacle opposed to the passage of electricity from a fluid to a solid conductor, is such, that when two metallic surfaces, either of the same or of different metals, are immersed in a fluid, so as to form a galvanic circle, that metal which transmits the electricity with the least loss of intensity is positive with respect to the other metal.*

(99.) The influence of this retarding cause varies also with the intensity of the current itself. The loss of electricity, from its passage through a number of metallic plates, is scarcely sensible when the current is very energetic, as, for instance, when it proceeds from a battery composed of a great number of plates; but it becomes more and more perceptible, according as the original intensity of the current is less considerable. It is also remarkable that the current is disposed to pass more readily through imperfect conductors, which present a great degree of resistance, when it has previously been made to traverse a great number of metallic plates. This was illustrated in two comparative experiments, in the first of which a current, originally of high intensity, was reduced, by passing through a considerable number of plates, till it was equal in intensity to one originally weaker, that had, in the second experiment, passed through a smaller number; of the two currents, thus apparently rendered equal in every respect, it was nevertheless found that the one which had previously passed through the greater number of plates, was thereby rendered capable of passing through any succeeding plate with less loss of intensity than the other current. The phenomena, he states, correspond to those which would take place, if we could imagine that there were two distinct kinds of electric current—the one capable of passing indiscriminately through all sorts of conductors, good or bad; the other capable of passing through good conductors alone. The passage of the currents through successive plates gradually effect the separation of these two portions, the plates arresting the one which cannot pass so readily through bad conductors, and giving free passage to the other portion.

(100.) M. De la Rive has applied this theory to the explanation of the different effects resulting from the increase of the number of the plates. If the pile, he says, consist only of a small number of plates, the electricity produced by it, not having undergone the above process of *filtration*, as it may be called, only one part of it will be capable of passing through an imperfect conductor, which is presented to it, and the other part will be arrested; but if a good conductor be presented, the whole of the electricity finds a ready passage, and will produce corresponding effects. Electricity of the former kind only will be capable of producing chemical decompositions, and of passing through organized bodies; but, in the latter case, it will be adequate to the production of all the calorific and magnetic effects. These modifications of electricity would, if this theory were established, have a remarkable analogy with those of light and of heat, under circumstances somewhat parallel.

(101.) It must be observed, however, that one source of the diminution of effect consequent on the multiplication of surfaces, exists in the transfer of elements which takes place in the fluid from galvanic action. This transfer, as is remarked by Sir H. Davy, in as far as it has actually occasioned the deposit of a positive element on the negative surface, and *vice versâ*, has an immediate influence in checking the further progress of the galvanic action; and arrests it completely when it has proceeded to a certain extent. Hence the powers of batteries are found to diminish by the continuance of their action, and ultimately to cease. This change we have already noticed in treating of the chemical actions of the simple galvanic circle. (§ 41.)

(102.) It is obvious that the several causes of retardation now stated render it exceedingly difficult to determine, previous to actual experiment, the relative powers of different batteries, composed of different materials, and consisting of different numbers of alternations of its parts.

(103.) It is not easy to understand the manner in which the chemical elements of a body decomposed by galvanism, are carried to their respective stations in the voltaic circuit. Thus if the influence of a powerful battery be transmitted through water, it will operate in decomposing that fluid, although the wires which form the communication with the poles be at a considerable distance from each other. They may even be placed in separate vessels, provided the portions of water in which

* *Annales de Chimie et de Physique*, xxxvii. 384.

they terminate are made to communicate with one another by means of a syphon full of water, or even by moistened threads. We find, under these circumstances, the whole of the oxygen of the decomposed water transferred to the positive, while the hydrogen is collected at the negative wire. Two questions may here be asked: first, in what part of the circuit does the decomposition take place? secondly, in what mode are the elements of the decomposed particles transferred to such distant points, without any indication being afforded of their movements, which must be exceedingly rapid, in order to traverse through so long a space? The velocity of this transfer would appear to be very considerable from the following experiment made by Dr. Roget, in the year 1807. The ends of two platina wires, communicating with the poles of a powerful battery, were introduced into two separate vessels of water, communicating by means of a long tube, bent into the form of a syphon, and filled with a solution of common salt. The whole length of the fluid part of the circuit between the two wires was 46 inches. Microscopes were applied to the ends of the wires, for the purpose of enabling the observer and an assistant, (who was the late Mr. Sylvester,) to ascertain the precise moment when the gases made their appearance at the respective wires. No sensible interval of time could be perceived between the appearance of the oxygen gas at the positive, and of the hydrogen gas at the negative wire, when the communications with the battery were made.

(104.) The transfer of material and ponderable substances, such as those which constitute the elements of water, might be expected, even with a moderate velocity, to occasion visible currents in the fluid through which they pass; for their motion, by whatever force produced, must be accompanied by a certain momentum, sufficient to displace the particles of the fluid through which they pass. Dr. Roget could, however, detect no appearance of current or displacement of fluid; such as would be indicated by movements among the minute globules of dust, or other extraneous matters suspended in the water, even with the assistance of the microscope. Mr. Wilkinson and Professor de la Rive, have also arrived at the same conclusion, by employing microscopes of high magnifying power

(105.) These phenomena of transfer have appeared to some so inexplicable, upon the commonly received doctrine of the composition of water, that they have had recourse to a new hypothesis in order to solve the difficulty. Professor Ritter was led to consider water as a simple substance, forming oxygen by its combination with positive electricity, and hydrogen by its union with negative electricity; and this theory was adopted by several other philosophers. Monge endeavoured to account for the phenomena, by supposing that water formed compounds with excess of oxygen on the one hand, or excess of hydrogen on the other; which compounds passed in opposite directions between the two wires, each depositing on their arrival the superabundant ingredient. Dr. Bostock conceived that the water was decomposed at the positive wire only, where its oxygen was disengaged; and its hydrogen, uniting with electricity, was carried invisibly along with it to the negative wire, where this union being dissolved, the electricity passed on through the wire, and the hydrogen appeared in its gaseous form.

(106.) The following mode of explaining these phenomena was suggested by Dr. Roget, in a paper which was read to the Philosophical Society of Manchester, in 1807.

"We may conceive the agency of electricity to extend throughout the whole of the fluid line connecting the two wires. The hydrogen existing in every particle of water in this line, will, if it possess a positive electrical polarity, according to the hypothesis of Mr. Davy, be repelled by the positive, and attracted by the negative wire. We may consider the row of particles of hydrogen abstractedly from those of oxygen. While the former are moving together, by the agency of the electricity, in a direction towards the negative wire, all those particles which have not yet reached that wire, will merely have to pass over in succession from one particle of oxygen to the next, among those of the other row. They will not appear in the form of gas, because the instant each has quitted the particle of oxygen with which it was associated, it meets with another to combine with; and this process will be continually repeated until it has arrived at the end of the line, when, finding no oxygen to unite itself with, it will make its appearance in the form of gas. In like manner, the first particle of hydrogen, in the series,

by its abandoning the first particle of oxygen, which finds no other particle of hydrogen to replace it, causes the oxygen to appear at that point in the form of gas. We have thus the two gases formed at each end, not from the same individual particle of water, but from the two which happen at that moment to be in contact with the wires. The production of the two gases will take place at the same instant in both places, each particle having only to move one step, that is, from one particle to the adjoining one, instead of having to traverse the whole extent of the line, and no current will be perceptible in the fluid. If this theory be correct, the operation of gravity in favouring the descending current of the heavier element, namely oxygen, might be rendered sensible; and that this is actually the case appears by an observation of Mr. Sylvester, that when the wire giving out oxygen is placed at a much lower level than that which gives out hydrogen, the effect is sensibly greater than when the positions are reversed."

(107.) Similar explanations of the mode of transfer have been given by Dr. Henry, and by Grotthus; and from the following passage in Sir H. Davy's last paper on the subject,* it would seem that he entertained views somewhat similar. "If it be supposed that the fluid is divided into two zones, directly opposite in their powers to the poles of the battery, the virtual change may be regarded as taking place in the two extremities of these zones nearest the neutral point; so that by a series of decompositions and recompositions, the alkaline matters and hydrogen separate at one side, and oxygen, pure, or in union, at the other. In this way the electricity may be regarded as the transporter of the ponderable matters, which assume their own peculiar characters at the moment when they arrive at the point of rest." That visible motions are sometimes produced in fluid conductors when transmitting the electric current, has been shown by Sir H. Davy, who noticed the very singular convulsive agitations into which mercury is thrown, when placed within the circuit of a powerful voltaic battery discharged through water.† These motions, which are frequently of a violent and capricious kind, have also attracted the attention of Mr. Herschel, and he has made them the subject of an interesting research, of which an account is contained in the Philosophical Transactions.*

(108.) The following singular fact has been noticed by Mr. Porrett:—If a vessel be divided by a membranous partition into two compartments, of which the one is filled with water, and the other contains but a very small quantity, and if the positive wire from a voltaic battery be inserted into the former, and the negative wire into the latter, the water will be impelled from the first compartment into the second, through the partition, and will at length rise to a higher level in the latter than in the former.† Mr. A. De la Rive, upon repeating these experiments, arrived at the same result, when he employed distilled or river water, which has but a small conducting power; when, however, a saline solution of sufficient strength was used, no such effect of impulsion was perceptible. But the reality of such an effect under the above circumstances, is sufficient to establish the existence of a mechanical force derived from the current of voltaic electricity.

(109.) We have already had occasion to observe that a theory, founded upon totally different views of the sources of galvanic power from those which have now been stated, has been applied to the explanation of the phenomena. As this, which has been termed the *electric theory of galvanism*, has been adopted by several eminent philosophers, it ought not to be considered as undeserving of notice in this place.

(110.) It was conceived by Volta, the original author of this theory, that the primary source of the electricity liberated during the action of a galvanic apparatus, might be traced to the contact of the dissimilar metals. He assumed as a fundamental fact, that during the whole time that these metals are in contact, a certain force is in constant operation, tending to effect a transfer of electricity from the one metal to the other. To this force he gave the name of *electromotive force*. When, for example, zinc and copper are in contact, the alleged operation of this force is to impel the electricity from the copper to the zinc, so as to maintain in the latter a positive state, when compared with the former, which will, consequently

* *Philosophical Transactions* for 1826, p. 416, 417.
† *Elements of Chemical Philosophy*, p. 173.

* For 1824, p. 163.
† Thomson's *Annals of Philosophy*, viii. 74.

itself be in a negative state with relation to the zinc. If either of these states be reduced to a more neutral condition by communication with other bodies; that is, if the redundant electricity of the zinc be carried off, and the deficiency of electricity in the copper be supplied from other sources, the electromotive force will, he conceived, immediately renew this difference of condition, and thus maintain a continual and rapid current of electric fluid, flowing always in the same direction.

(111.) It was further assumed in this theory that liquids have no electromotive power when in contact with metals: and that this negative property enabled them to transmit the electricity evolved by the contact of the zinc and copper, and which is accumulated in the zinc, back again to the copper; whence it is again transferred to the zinc; and so on in a perpetual circle. In compound galvanic circles, the electromotive force residing in the surfaces of contact between the two metals in each pair of plates, are all tending in the same direction; and the several impulses they give to the electricity conspire together to increase the effect, which will therefore be the sum of all the forces taken separately. Thus will a continued and powerful stream of electricity be determined from the negative to the positive pole of the battery, ready to circulate through any conducting line of communication extending between the two poles. The office of the fluid is considered, in this theory, as simply that of conducting the electricity from the one metal to the other: its chemical action on either of these being regarded as a mere accidental circumstance, not in any way concerned in the production of galvanic or electrical effects. The effective quantity of electricity which actually circulates in the voltaic battery is supposed to be determined altogether by the degree of conducting power possessed by the liquid: for it is assumed that the quantity which the electromotive force existing at even the smallest surface of contact between dissimilar metals could set in motion, if the movements of that electricity were not impeded by the difficulty of its transmission through fluids, would be incomparably greater than that which any conducting fluid can discharge.

(112.) Such is the general outline of the electric theory, which it is scarcely necessary to pursue in its various applications, because there are several facts which appear so totally at variance with the immediate consequences of its fundamental hypothesis, as to warrant us in rejecting it. Chemical action between some of the elements of a galvanic combination is so invariably connected with the production of electrical effects, that it would be a violation of all just rules of philosophy not to consider these two classes of phenomena as standing to each other in the relation of cause and effect. The quantity of galvanic effect is always in proportion to the energy of the chemical action. The extent of contact between the two metals, on the other hand, appears to have no relation to the quantity of electricity which is developed. Combinations producing galvanic effects may be formed, as we have seen, with a single metal only, when two fluids are present; and indeed, on other occasions, without the presence of any metallic substance whatever. We have also seen that the same metals do not in all cases stand in the same invariable electrical relation to each other; but that this relation is determined by the chemical properties of the fluid with which they are placed in contact. (§ 75.) All these facts are irreconcilable with the electric theory.

(113.) Were any further reasoning necessary to overthrow it, a forcible argument might be drawn from the following consideration. If there could exist a power having the property ascribed to it by the hypothesis, namely, that of giving continual impulse to a fluid in one constant direction, without being exhausted by its own action, it would differ essentially from all the other known powers in nature. All the powers and sources of motion, with the operation of which we are acquainted, when producing their peculiar effects, are expended in the same proportion as those effects are produced; and hence arises the impossibility of obtaining by their agency a perpetual effect; or, in other words, a perpetual motion. But the electro-motive force ascribed by Volta to the metals when in contact, is a force which as long as a free course is allowed to the electricity it sets in motion, is never expended, and continues to be exerted with undiminished power, in the production of a never-ceasing effect. Against the truth of such a supposition, the probabilities are all but infinite.

MAGNETISM

CHAPTER I.

General Facts and Principles.

(1.) THE attractive power of the loadstone for iron was known in times of very remote antiquity, and has been, in all ages, a subject of curiosity and of wonder. It is a property which seems, at first sight, so unconnected with every other, as to form of itself a separate class among natural phenomena: and, although an immense mass of knowledge relating to Magnetism has been accumulated by the labours of successive generations, and embodied into a science of high rank and importance, yet the field it comprises is of comparatively limited extent. This arises from the great simplicity which characterises both the phenomena and the laws that govern them; a quality, however, which peculiarly invites a philosophic mind to undertake their investigation. A still more powerful motive to this inquiry will present itself when we reflect on the signal benefits mankind has derived from magnetism as applied to the purposes of navigation. The discovery of the compass, by the aid of which, the mariner, however distant from land, amidst cloudy skies, or in the darkest nights, is enabled, at all times, to steer his course with certainty, and traverse in all directions the wide expanses of ocean which separate the countries and continents of our globe, must unquestionably rank among the great discoveries that have essentially contributed to advance the civilization of the human race.

(2.) The term MAGNETISM expresses the peculiar property occasionally possessed by certain bodies, more especially by iron and some of its compounds, whereby, under certain circumstances, they mutually attract or repel one another, according to determinate laws.

(3.) This property was first noticed in a mineral substance called the *native magnet*, or the *loadstone*, which is an ore of iron, consisting chiefly of the two oxides of that metal, together with a small proportion of quartz and alumina. Its colour varies in different specimens, according to minute differences in the proportion of the oxides, and the nature of the other substances with which they may be found united: but it is usually of a dark grey hue, and has a dull metallic lustre. It is found in considerable masses in the iron mines of Sweden and Norway, and also in different parts of Arabia, China, Siam, and the Philippine Islands. Small loadstones have occasionally been met with among the iron ores of England.

(4.) There are several modes in which a piece of iron may be rendered magnetic, or converted into what is called *an artificial magnet;* and for all purposes of accurate experiment such a magnet is much to be preferred to a loadstone. The following is a simple and ready method of obtaining artificial magnets with a view to the investigation of the magnetic properties.

Let a straight bar of hard tempered steel, devoid of all perceptible magnetism, be held in a vertical position (or still better, in a position slightly inclined to the perpendicular, the lower end deviating to the north,) and struck several smart blows with a hammer; it will be found to have acquired, by this process, all the properties of a magnet.

(5.) These properties are the four following:—viz. 1. Polarity. 2. Attraction of unmagnetic iron. 3. Attraction and repulsion of magnetic iron. 4. The power of inducing magnetism in other iron. These we shall now explain and illustrate.

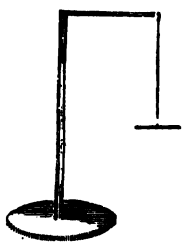
§ 1. *Polarity.*

(6.) If a bar, which has been rendered magnetic, be supported in such a manner as to have entire freedom of motion in a horizontal plane, and be removed from the neighbourhood of all ferruginous bodies which might influence it, it will spontaneously turn round, and, after a few oscillations, will finally

settle in a position directed nearly north and south. If it be disturbed from this situation and placed in any other direction, it will, as soon as it is again at liberty to move, resume its former position. The end of the bar which points to the north, is that which was lowermost at the time it acquired its magnetism by hammering: the end which, during that operation, had been the upper one, is consequently that which, when the magnet is free to move, directs itself to the south. The two ends of a magnet of this form are called its *poles:* the one which spontaneously turns to the north, being distinguished as the *north*, and the other as the *south pole:* and the tendency of the magnet to assume the above described position is called its *Polarity*. The straight line joining the two poles of a magnet is called its *axis*.

(7.) There are several ways of supporting a magnet so as to enable it to manifest its polarity. The readiest mode is to suspend it by a thread, fastened

Fig. 1.



round it at the middle, so that it may be sufficiently balanced to preserve its horizontal position as it turns freely round its centre. It cannot, indeed, turn thus, without, at the same time, either twisting or untwisting the thread by which it hangs; and the reaction of the thread, the fibres of which tend to resume their original situation, or the force of torsion, as it is called, may prevent the magnet from assuming the precise position to which its polarity would have brought it. But by employing a very slender thread, and taking it of sufficient length, the force of torsion may be so much reduced as to be quite insensible in the experiments about to be described.

(8.) Another convenient mode of examining the horizontal movements of the magnetized bar is to poise it on its centre, hollowed into a cap, which is made to rest on a fine point fixed in a stand.

Fig. 2.

When thus fitted up, it acts like the needle of a mariner's compass; and in its principle is identical with that instrument.

(9.) We may sometimes find it more expedient to fix the magnet on a piece of cork, and thus make it float on water,

Fig. 3.

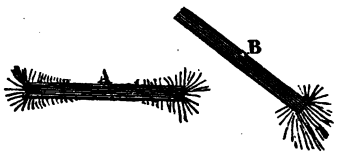
in a basin. In this case, we must take care, however, that it be kept at a sufficient distance from the sides of the vessel to prevent its being affected by the capillary attractions of the water.

The same precaution must be used if the magnet be made to float on the surface of mercury, which is an excellent mode of giving it complete liberty of motion. But the vessel containing the mercury should be at least six inches in diameter, in order to guard against the effects of the curvature of the surface of the mercury near the sides. When the surface of the mercury is very clean and bright, which happens only when the metal is very pure, it allows of the ready motion of pieces of iron floating upon it. But it soon tarnishes, and the film of oxide which forms on the surface, becomes a great impediment to the freedom of motion of the floating body. The best way of rendering it clean, is to strain it through a funnel of paper rolled up into a cone, having a small aperture at the point, of about the fortieth of an inch in diameter.

§ 2. *Attraction of Iron.*

(10.) If either pole of a magnet be brought near any small piece of soft unmagnetic iron, it will be found to attract it. Iron filings, for instance, are immediately collected together when a magnet is placed among them; and they adhere more especially to the poles (as shewn in *fig.* 4, A), from which,

Fig. 4.



when the magnet is lifted up, they remain suspended in thick clusters. (*Fig.* 4, B.) A small number of filings are also found adherent to the intermediate parts of the bar, but they are evidently attracted much more feebly than those at the ends; it may also be remarked that there is a part of the magnet, generally mid-way between the two ends, to which the filings have no tendency to adhere at all, and which appears therefore to have no power of attraction. Thus it appears that the attractive forces, whatever be their nature, reside chiefly at the poles.

(11.) It is an established law of nature, the knowledge of which we have derived by induction from a vast variety of phenomena occurring in every part of the material universe, that all *action* is attended by a corresponding *reaction*, equal in degree, but opposite in its kind, to the action itself. Mechanical philosophy, in all its departments, abounds with exemplifications of this fundamental principle; many of these, indeed, are matters of familiar observation. The stretched rope pulls back with equal force at both its ends; the compressed spring resists equally in two opposite directions; the exploding powder, at the same moment that it propels the ball, gives to the gun its recoil. In all the effects resulting from cohesion, from elasticity, from caloric, from animal force, from gravitation, whether actuating the minutest particles of matter, or the largest masses; whether exerted on the rolling waters of the ocean, or displayed on the grander scale of the planetary movements, the same universal law is rigidly observed. To every physical force there is opposed another and a similar force. No material agent can produce an effect upon another, without being at the same time subjected to an equal reaction from that other agent. An attracting body must of necessity be itself attracted, and a repelling body repelled. This perfect reciprocity of action takes place in all the agencies of electricity;—it exists also in those of magnetism.

(12.) If the two bodies exerting a mutual action upon one another, be very different in their size, the smaller of the two will necessarily exhibit the effects of this action more strongly than the larger, because, its mass being less, the same force will communicate to it a greater velocity of motion. We find, accordingly, that the small fragments of iron in the experiment just described, appear to fly towards the magnet, while their reciprocal action on the magnet itself is imperceptible. But this latter action may be rendered sensible by trying its effect on a magnet poised or suspended in any of the ways above mentioned; and we shall find that on presenting a piece of soft iron to either of the poles of the magnet, the latter is slowly attracted by the iron. The attraction, therefore, between the magnet and the iron is reciprocal.

Let us next see what influence magnets have upon one another.

§ 3. *Attraction and Repulsion of Magnetic Iron.*

(13.) For the purpose of examining the mutual action of two magnets, we may either present to the poised magnet another magnet held in the hand, or we may place two poised magnets in different positions with respect to each other. We shall find by sufficiently varying these positions, that when the poles of different magnets are brought near one another, they in some cases appear to be attracted towards each other, while in others they manifest a mutual repulsion. This, however, does not happen capriciously; for if we mark the poles according to the distinction already pointed out, we shall find that two north poles always repel each other: —that two south poles also repel each other:—but that the north pole of one magnet invariably attracts, and is of course attracted by the south pole of another magnet.

(14.) It thus appears that there are two species of magnetic powers, the northern and the southern, which in their mode of action are perfectly similar, but in their effects are directly opposite.

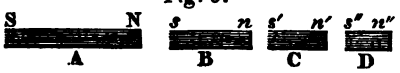
(15.) Such of our readers as have studied our Treatise on Electricity must here be struck with the pointed analogy which subsists between the phenomena of magnetic attraction and repulsion, and those of electricity. In both there exists the same character of double

agencies of opposite kinds, capable, when separate, of acting with great energy, but being, when combined together, perfectly neutralized and exhibiting no sign of activity. As there were two electrical powers, the positive and the negative, or, as some prefer denominating them, the vitreous and the resinous, so there are two magnetic powers, distinguished as the northern and the southern polarities; or, as some choose to designate them, the austral and the boreal. The parallel is most exact. Both sets of phenomena are governed by the same characteristic law, which may be expressed by the following concise and general formula, namely, —between like powers there is repulsion; between unlike, attraction.

§ 4. *Induction.*

(16.) The communication of magnetic properties to iron or steel by the mere approach of the poles of a magnet, is also analogous in its principal circumstances to electric induction.

Fig. 5.



If the north pole, N, of a magnet A (*fig.* 5), be brought near to the end *s* of an unmagnetized bar of iron, B, that end will immediately acquire the properties of a south pole, while the opposite, or distant end, *n*, will at the same time be converted into a north pole. If, instead of the north pole, N, the south pole, S, had been presented to the bar, the changes effected in B would have been just the reverse; the adjacent end would have acquired the northern, and the distant end the southern polarity.

(17.) Thus we may observe that each pole of a magnet induces the opposite kind of polarity in that end of the iron which is nearest to it, and the same kind on the remotest end; just as happens in the induction of electricity, in which the positive state induces the negative, and the negative the positive state, in those parts of an insulated conductor which are nearest to the electrified body; and a similar state of electricity in the distant end.

(18.) That the iron, while it remains in the vicinity of the magnet, possesses the magnetic properties, may be shown by a variety of experiments.

First, it attracts other iron. If we take, for instance, a key (*fig.* 6), and

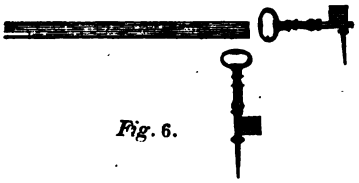


Fig. 6.

hold it horizontally near one of the poles of a strong magnet, also lying in a horizontal position, but not touching the key; and if we then apply another light piece of iron, such as a small nail, to the other end of the key, the nail will hang from the key, and will continue to do so while we slowly withdraw the magnet horizontally from the key. When the magnet has been moved beyond a certain distance, the nail will drop from the key, because the magnetism induced on the key becomes, at that distance, too weak to support the weight of the nail. That this is the real cause of its falling off may be proved by taking a still lighter fragment of iron, such as a piece of very slender wire, and applying it to the key. The magnetism of the key will still be sufficiently strong to support the wire, though it could not support the nail: and it will continue to support the wire, even when the magnet is yet further removed; at length, however, when the distance is still greater, the wire, in its turn, drops off.

The same effects may be observed if the nail be placed in contact with the near end of the key; but they are generally less distinct, on account of the direct influence which the magnet exerts on the nail, and which interferes in some degree with the action of the key, so that the results become complicated.

(19.) The same series of phenomena take place when the key is held above or below the pole of the magnet, or on either side of it. The key will hold the nail or wire suspended from either end, as long as the magnet is near enough to exert sufficient influence on the key.

(20.) If the key be laid upon a piece of paper on a table, and several small bits of wire, or iron filings, be strewed round one end of the key, which we suppose to be devoid of all magnetic properties, no adhesion will be perceptible between the fragments of iron and the key. Let us now approach the pole of a magnet to the other end of the key; we immediately observe the filings and lighter pieces of iron spontaneously, and of one accord, move towards the key, and

adhere to it just as if the key had itself become a magnet. They also collect and cohere together, as if animated by a common sympathy. When this has taken place, let us suddenly remove the magnet: that moment all these effects cease at once, the key returns to its natural or unmagnetic state; the bits of iron which had attached themselves to it immediately fall off, and show no tendency either to cohere among themselves, or to adhere to the key.

(21.) Secondly, the vicinity of a magnet to a piece of iron gives it the property of attracting and repelling the respective poles of another magnet, in the same way as a magnet would have done. The truth of this proposition may easily be proved by placing a small compass needle poised as in *fig.* 2, in various situations relative to the ends of the key or any other piece of iron of a lengthened shape, while in the vicinity of the magnet. It will be seen by this examination that the piece of iron has acquired by induction two poles, the qualities of which will be discovered by their attractions or repulsions of the poles of the compass needle, as they are respectively presented to each; and it will be found that these two poles are disposed in the manner specified above.

(22.) Thirdly, the iron, which has become magnetic by induction, has at the same time acquired the power of inducing a similar state of magnetism on the iron in its neighbourhood. Thus, while the bar B, *fig.* 5, is rendered magnetic by the influence of the magnet A, it exerts itself a similar power on another bar C, rendering it also magnetic. The bar C, in its turn, will act in like manner upon another bar, D, and so on. In this way the influence of the magnet A may be made to extend along a series of iron bars or pieces of any other shape, each acquiring magnetism by the inductive power of the preceding piece; and in its turn inducing magnetism on the next.

(23.) But this is not all. The piece of iron which has been rendered magnetic by the vicinity of a magnet, not only acts upon the other iron that is near it, but also reacts upon the magnet from which its power is derived, and increases the intensity of its magnetism. The power of a magnet is, in fact, augmented by the exertion of its inductive influence on a piece of iron in its neighbourhood. A simple experiment is sufficient to prove this fact.

Let a piece of iron be suspended from one of the poles of a straight magnet; and let the weight which this magnet will carry be ascertained by attaching to the iron a scale, capable of holding the weights necessary for this trial, and which may be gradually increased till the piece of iron drops off from the magnet. Repeat this experiment, having previously placed a bar of iron in contact with the other pole of the magnet, and it will be found that the magnet will now support a much greater weight; showing the increase of power it has derived from the presence of the bar of iron which has been applied to the other pole, and the induced magnetism of which, although solely derived from the magnet, reacts, by a kind of secondary induction, upon that magnet. We have already had occasion, in the Treatise on Electricity, to notice the same kind of reaction in the case of electric induction. The increased intensity which a magnet acquires by induction often leads to the permanent acquisition of power by the magnet. Hence we may understand the reason why a magnet that is employed for magnetizing a neutral bar of steel, by means of its inductive power, becomes itself stronger by the operation.

(24.) It is a necessary consequence of the law of magnetic induction that it is accompanied by attraction: for the polarity of the adjacent end of the piece of iron on which the magnetism is induced, is always of the opposite kind to that of the pole of the piece which induces it: according to the fundamental law of magnetism, therefore, a mutual attraction must take place between them. The remote end of the piece on which the magnetism has been induced is indeed repelled, because its polarity is similar to that of the inducing pole: but it is evident that the attractive action of the adjacent and dissimilar poles will always be stronger than the repulsive action of the more distant poles; and will therefore always prevail.

(25.) This remark leads us to a very important step in the generalization of the magnetic phenomena. We have hitherto spoken of the attractive power of magnets for iron as one of the primary facts in the science: but we now see that it is merely a necessary result of a more general law, namely, that of induction, together with the law of action of the two polarities upon each other:—or, in other words, that it is itself comprehended in these more general facts. A magnet attracts a piece of unmagnetic iron, not from any inherent disposition to attract it in that state, but in

consequence of its inductive influence, which converts it, for the time, into a second magnet, having its poles so disposed with relation to the first magnet, that the adjacent parts have always opposite polarities; and attraction, therefore, takes place between them. Thus the pieces A and B, *fig.* 5, attract each other, simply because the induced magnetism of the end *s* is of the opposite kind to that of the pole N. In like manner B and C attract each other, because the polarities of the adjacent poles *n* and *s'* being of a dissimilar kind, their mutual action is attraction. With respect to this ultimate effect, the inductive influence of either pole is exactly alike, and leads to the same result.

(26.) We may now understand the reason why, when a magnet is placed in a heap of iron filings, and then lifted up, the filings attach themselves in clusters to the poles, arranging themselves in lines, and adhering together by a force of attraction which extends from each individual particle to those which precede and follow it. They form, indeed, by their mere juxtaposition, under the influence of the large magnet, a series of minute magnets, of which the poles are similarly situated in each, and being alternately north and south, the adjacent ends attract one another.

(27.) This disposition of the poles may be verified by making an experiment of the same kind on a larger scale, suspending from the end of a strong magnet a piece of iron, such as a key (*fig.* 7), from the lower end of which a smaller key may be made to hang in consequence of its induced magnetism. To this may be appended a still smaller piece of iron, such as a nail; and we may thus proceed, adding piece after piece, till the lower one will exert only sufficient attraction to sustain a very small weight of iron, such as a small needle. The polarities of the lower ends of each piece, if examined previously to each additional piece being appended to it, will be found to be constantly of the same kind as that of the lower end of the magnet from which the whole is suspended. This may be ascertained by its attracting or repelling the poles of a small magnetic needle balanced on a point, and supported on a stand, as shown at M, *fig.* 7.

Fig. 7.

(28.) The knowledge of the general fact, that magnetic induction always tends to produce attraction between the adjacent parts of the bodies which act upon each other, enables us to explain many phenomena, which might otherwise appear to be at variance with the simple laws of attraction and repulsion already stated. Thus we find that the dissimilar poles of two magnets attract each other with a force which is greater than the repulsion exerted between the similar poles of the same magnets; and this happens because, in the former case, the tendency of induction is to strengthen the magnetic power of the adjacent dissimilar poles; but, in the latter case, where the poles are similar, each pole tends, by its inductive influence, to weaken the magnetism of the other. This is exemplified in a still more striking manner, when a weak magnet is brought near to a much more powerful one: in which case we find that, although when they are at a moderate distance from each other, either pole of the weaker magnet is repelled by the similar pole of the strong one; yet, if it be brought very near, and especially if it be made to touch the latter, it is attracted, and will even adhere with some force to the strong magnet. This effect evidently results from the powerful inductive influence of the strong magnet, which, for the time, destroys the feeble polarity of the weak magnet at the part immediately adjacent, and impresses upon it a polarity of an opposite kind: whence attraction follows as a necessary consequence of contrary polarities.

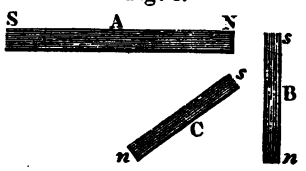
(29.) The intensity of magnetic power developed by induction in an iron bar, was found by Mr. W. S. Harris to be inversely as the distance of the inducing pole from the adjacent end of the bar on which it acts. It would also appear, from the experiments of the same gentleman*, that the intensity of the magnetism induced on the remote end of the bar, is, with the same inductive power acting on the nearer end, inversely as the length of the bar.

Magnetic induction is not confined in its operation to any particular direction; thus a bar of iron will be rendered magnetic if placed at right angles, or at any other inclination to the axis of the mag-

* Transactions of the Royal Society of Edinburgh for 1829.

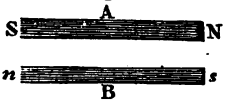
net, or line joining its two poles, as in the situations represented in *fig.* 8. The

Fig. 8.



ends, *s*, *s*, of the bars B, C, adjoining the north pole N of the magnet A, will still become south poles by induction, and the ends *n*, *n*, north poles. Under these circumstances, if the inclination be less than a right angle, as in the case of C, the opposite pole of the magnet *s* begins to exert an inductive influence on the other end of the bar *n*, which concur with that of the pole N in rendering *n* a north and *s* a south pole. The most favourable position for the bars receiving the full inductive influence of both poles is that of parallelism with the magnet A, as shown in *fig.* 9.

Fig. 9.



(30.) Complicated effects result from bringing the magnet in contact with other parts than the ends of a piece of iron. Thus, if the north pole of a magnet be placed in the middle of an iron bar, as in *fig.* 10, both extremities of the bar are rendered north poles, while the middle is a south pole.

Fig. 10.

(31.) If the north pole of a magnet be placed on the centre of a round iron plate (*fig.* 11), so that its axis may be

Fig. 11.

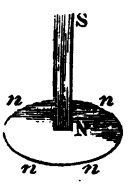
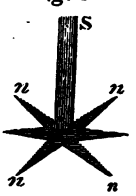


Fig. 12.

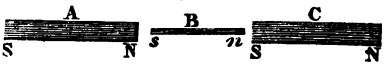


perpendicular to it, the plate will have a south pole in its centre, and every part of its circumference will have the properties of a weak north pole. If the plate have the form of a star (*fig.* 12), each of the points will have a stronger northern polarity than in the last case. Analogous effects may be observed in pieces of iron of an irregular shape when acted upon by a magnet; the part immediately adjoining to the north pole of the magnet acquires the properties of a south pole, and all the remote protuberances have a feeble northern polarity.

§ 5. *Complex Induction.*

(32.) When two magnets are placed so as to exert an inductive influence on the same bar, it will depend on their relative position, whether they shall conspire to produce the same polarities in the ends of the bar, or whether they shall oppose each other, and produce contrary polarities. If the bar B, *fig.* 13, lie between the two magnets A and

Fig. 13.



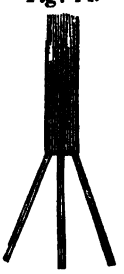
C, and be in the same line with them, and if N, the north pole of A, be adjacent to S, the south pole of C, the intermediate bar B will receive a magnetism of the same kind from the inductive power of both the magnets, its south pole *s* being adjacent to N, and its north pole *n* to S. Its magnetic power will, therefore, be considerably greater from the united influence of the two magnets, than it would have been from the influence of one only.

(33.) It may here be observed that the order in which the poles of these pieces A, B, and C, succeed one another, is exactly the same as that which obtains in the successive induction of magnetism along a series of iron bars, as in *fig.* 5. Now the same consequences follow from this arrangement in the one case as in the other. We have just seen that when C is a bar already rendered magnetic, the magnetism of the iron bar B, which the magnet A had induced upon it, is increased by the presence of C. In like manner, we find that the magnetism of the bar B, in the case above referred to, *fig.* 5, is increased by the presence of another piece of iron C, placed at its end, although that piece, previously to its being so placed, was entirely free from magnetism. This increase is owing to the piece C having become magnetic by its position with respect to B, which had itself been rendered magnetic by the vicinity of the magnet A. C having thus become a temporary magnet by

the action of B, reacts upon B, and, exerting a new inductive influence, tends to increase its magnetism in the same manner as if it had been a permanent magnet. Thus it is that in a series of iron bars held together by induced magnetism, each piece tends to increase the strength of the preceding piece, and the whole coheres together with greater force than if no such reaction took place. This circumstance affords a further explanation of the strong cohesion we observe among the particles of iron filings, which hang in long threads from the poles of a magnet.

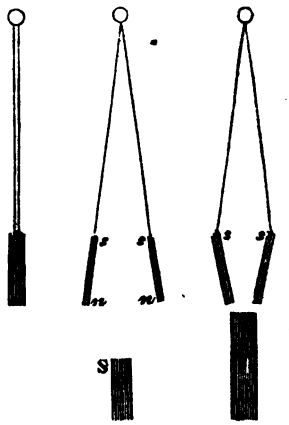
(34.) A closer attention to the consequences which flow from magnetic induction, will also enable us to explain another remarkable fact, which the adhesion of the strings of iron filings presents. It is that each separate filament, although composed of parts that attract each other in the direction of their length, yet shew a tendency to keep distinct from the neighbouring filaments, and even appear to repel one another. In order to understand this, let us consider the condition of several slender iron bars placed side by side, and adhering to the north pole of a magnet, as shewn in *fig.* 14. The inductive power of the magnet, as we have seen, will render each of the ends in contact with that pole, a south pole, while all the remote ends will be north poles. Hence, the bars will all have their similar poles near each other, and this will happen at both their extremities, and they will accordingly repel one another. As long as they adhere to the magnets by one end, this repulsion will be prevented by that adhesion from shewing itself; but at the other ends, which are at liberty to move, it will be strongly manifested, and the bars will be observed to separate or diverge from one another. Now this is very nearly the condition of the filaments composed of particles of iron. The polarities of those parts of each which are in contact, are neutralized and become scarcely sensible; but those of the extremities, being uncompensated, exert their full power, and produce the observed repulsion of the filaments.

Fig. 14.



(35.) This effect of induction is exceedingly well illustrated by the following experiment of Cavallo: let two short pieces of iron wire, *fig.* 15, be each fastened to a thread, the threads being joined at their other ends and formed into a loop, by which they are to be suspended from a hook or pin, so as to have full liberty to move. On bringing the pole of a magnet, the south pole for instance, at a certain distance below the wires, it will occasion them to recede from each other, as shewn in *fig.* 16, indicating the repulsion which takes place between the adjacent ends of the wires, in consequence of their being similarly affected by the inductive power of the magnet; the lower ends of both being rendered north poles, and the upper ends south poles. This divergency of the wires will continue to increase until the magnet has approached to a certain limit. But if the magnet is brought nearer than this limit, its own attractive force becomes so strong as to overpower the repulsion that exists between the lower ends of the wire; and therefore brings them nearer to each other, as shewn in *fig.* 17; while the repulsion of the upper ends *s*, *s*, still continues to manifest itself, by keeping them remote from one another. On removing the magnet entirely, the wires immediately collapse, their magnetism being only of a transitory nature. But if the same experiment be made with sewing needles, instead of soft iron wires, the needles will often continue to repel each other after the removal of the magnet, having acquired some degree of permanent magnetism by the circumstances in which they have been placed.

Fig. 15. *Fig.* 16. *Fig.* 17.



(36.) If four wires be suspended in a manner similar to those in the last ex-

periment, each by its separate thread, the induction of a similar magnetism upon all of them will produce a mutual repulsion among them, and they will of course all diverge from one another. But if the wires be made of steel, so as to retain whatever magnetism may be communicated to them, and a northern polarity be given to the lower ends of two of the wires, but a southern polarity to the lower ends of the other two wires, when each of these pairs is kept apart, the wires will repel each other; but if both pairs are brought together, all the four wires will unite and adhere together. The reason is that those wires which have opposite polarities attracting each other, unite to form a pair in which the polarities are balanced, and the repulsion each had before exerted towards those which were similar in the other pair, is now entirely neutralized. The same thing will happen, however numerous are the pairs of wires that are dissimilarly magnetized.

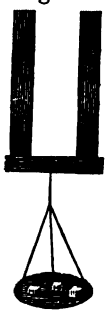
(37.) In order that a bar of iron may receive the combined inductive influence of two magnets, it is not necessary that they should all be situated in the same line as in the example already given. The same effect will result if the bar be at right angles to the two magnets, as in the following figure (18), provided the

Fig. 18.

two ends be immediately acted upon respectively by the poles of opposite denominations of the magnets. The attraction of a bar in this situation is much increased by the conspiring inductive influence of the two magnets; and the force exerted is more than double of that by which it would have adhered to either of the magnets when singly employed. This may be verified by attaching the scale of a balance to the bar (*fig.* 19,) and adding weights till its adhesion to the magnets is overcome: these weights will be found to exceed the sum of the weights which the two magnets would have supported, by means of the adhesion of the same iron bar, if they had been applied separately

(38.) While such is the effect of the application of the dissimilar poles of two magnets to the ends of a bar of iron, namely, that of conspiring to induce the same kind of magnetism, it is likewise evident that an effect of an opposite kind must result when the dissimilar poles of

Fig. 19. *Fig.* 20.



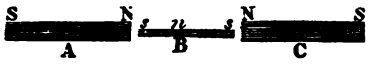
the magnets are both applied to the same end of a bar. These poles, being of different kinds, will produce contrary effects; their inductive influence will oppose, instead of assisting, each other, and the magnetism induced on the bar will be only that resulting from the difference, instead of the sum of their intensities. If the bar be of some length, and if the magnets be of equal strength, and applied close to each other, their actions upon the remoter parts of the bar will be so nearly equal, that they will almost entirely neutralize each other, and no sensible degree of magnetism will be excited. Thus if while a key is supported by a magnet as in *fig.* 20, we gradually bring down upon it a second magnet, with its lower pole of the opposite kind to the lower pole of the first magnet, it will tend to induce in the key a polarity of an opposite kind to that which it has received from the first magnet. In as far as it exerts that influence it diminishes this magnetism, and consequently weakens the attraction. Another cause also operates in diminishing the attraction. The polarity induced upon the adhering end of the key is of the contrary kind to that of the pole of the first magnet; it is therefore of the same kind with that of the second magnet which is brought near it, and which, therefore, as far as the key retains its induced magnetism, must repel it. Accordingly, it happens that when the second magnet, if sufficiently powerful, is brought within a certain distance from the upper end of the key, it destroys its power of adhering to the magnet, and the key drops off.

A similar counteraction of magnetic induction will take place, when the other pole of the second magnet, that is the

pole of the same denomination as that of the first magnet to which the key adheres, is applied to the lower end of the key. The first action of the lower magnet, as it approaches the key under these circumstances, is to repel it; but on being brought still nearer, its inductive influence becomes so great as to reverse the poles of the key, which is now attracted by the pole which before repelled it: it then generally drops off and adheres to the lower magnet.

(39.) The effect of applying similar poles to the two ends of a bar of iron is generally that of inducing the opposite polarity on both ends of the bar, and the same polarity at the middle. Thus, *fig.* 21, the north poles N, N, of the two mag-

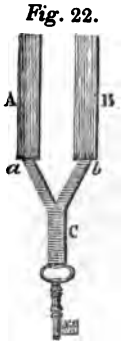
Fig. 21.



nets A and C being applied lengthwise to the ends of an intermediate bar B, will render it a magnet with three poles, those at the end being south poles, and the middle being a north pole. In this case the bar will be attracted by both the magnets, though less powerfully than when the acting poles of the latter are of opposite kinds, as in the situation shewn by *fig.* 13. In more complicated cases, and more especially when the form of the piece of iron is irregular, it is difficult to predict the exact mode in which the poles will arrange themselves when magnetism is induced upon it by a single magnet, and still more when the operation of two or more magnets, especially if they be of unequal strength, is to be estimated. The following, however, is one of those cases in which the process that takes place is more obvious, and which furnishes an amusing illustration of the general principle.

(40.) Take a piece of iron, C (*fig.* 22), formed into the shape of a fork, or of the letter Y, and suspend it by one of the branches of the fork to the north pole of a magnet A; its lower end will immediately acquire a northern polarity, and will attract another small piece of iron, such as a key, which may therefore easily be supported by it. While the key is thus hanging from its lower end, apply to the other branch of the fork the south pole of another magnet B, the key will instantly drop off. The reason is that the magnet B tends to induce upon the remote or lower end of the fork, a contrary polarity to that which is induced upon it by A, and thus destroys its power of attracting. The fork will have a south pole at *a*, a north pole at *b*, while its lower end will be neutral. If, on the contrary, the north pole of the magnet B had also been applied to the branch *b* of the fork, its influence would have conspired with that of A in inducing a northern polarity at C, and the key would have been more strongly attracted.

Fig. 22.



§ 6. *Different Qualities of Iron and Steel with regard to Magnetic Susceptibility and Retentiveness.*

(41.) All the effects we have hitherto described, as attendant on the induction of magnetism on iron, are of a temporary nature, depending altogether on the influence excited by the neighbouring poles of a magnet; for we find that, the moment the magnet is removed, all these effects cease, and the iron returns to its original state of neutrality, and loses all its magnetic properties. But the case is different when steel is made the subject of experiment. Magnetism, it is true, may be induced on steel; but the induction proceeds very slowly, and is, at first, much more feeble than it is with iron. On the other hand, steel does not, like iron, lose what it has acquired; for, on the removal of the magnet which gave it the magnetic properties, it retains these properties permanently: it has, in fact, become itself a real magnet.

(42.) This remarkable difference existing between iron and steel in their respective susceptibility to receive, and capacity to retain magnetism, must, no doubt, arise from some peculiar arrangement of their particles, the exact nature of which is at present entirely unknown.

It is, however, exceedingly analogous to the difference in the qualities of electrics and non-electrics with regard to the power of conducting electricity; and the magnetic phenomena depending upon it admit of being explained on an hypothesis very similar to that by which we are enabled to account for the electrical phenomena which correspond to them. The two magnetic polarities may be conceived to reside constantly in all iron or steel, and in the natural or neutral condition of these bodies, may be regarded as in a state of equilibrium,

and as equally distributed throughout the whole mass. But this state of equilibrium in a bar is disturbed by the influence of a magnetic pole in the vicinity, which exerts an inductive influence. This new force which comes into play, tends to transfer one kind of polarity to one end of the bar, and the opposite polarity to the other end. In iron, these changes are readily effected, on account of the facility which its peculiar texture affords for the transmission of these agencies in both directions. No sooner is the cause which has produced these changes, and maintains the separation of the polarities, removed, than all the effects cease; for there exists no obstacle to the return of the two polarities to their original situations: they revert, therefore, to their former state of equal distribution, and the condition of neutrality is restored in every part. But it is not so with steel; the constitution of which is such as to interpose impediments to the transfer of the polarities from one part to another. It requires a certain time before the obstruction, whatever be its nature, can be overcome; and before the new state of distribution, which induction tends to establish, can be completed; nor can the changes themselves ever be accomplished to the same extent as they are in bodies which present no such obstacles. It is also a necessary consequence of the resistance which the texture of steel presents to any changes taking place in its magnetic condition, that these conditions, when once induced, tend to remain in a great degree fixed. Hence we see the reason why steel bars admit of being rendered permanently magnetic, while the magnetism induced upon iron is only temporary. A steel bar, which has as great a degree of magnetic power as it is capable of retaining, is said to be *saturated* with magnetism.

(43.) In order to obtain an exact knowledge of the progress of magnetic induction in steel, we should place a bar of this material very near to the pole of a strong magnet, and in the same line with

Fig. 23.

it, and provide ourselves with a very small and delicate compass needle, poised on its centre, as in *fig.* 2, by which the polarity of each part of the bar may be examined in succession. It will be evident that an inductive action commences immediately on the magnet's being presented to the bar; for the latter is attracted and adheres very strongly to the magnet from the very first.

The end next the magnet has, therefore, acquired a polarity of a contrary nature to that of the magnet. For the sake of greater clearness of illustration, we shall suppose the actual pole of the latter to be a north pole. The near end of the steel bar is at once converted into a south pole; but if we examine the remote end we do not find it so immediately converted into a north pole. A sensible time is required for effecting the change in the latter; and it will be found, upon a more careful investigation, that the different parts of the bar from south to north, acquire, in succession, this northern polarity, which at last settles in the extremity. If the bar be of considerable length, it

Fig. 24.

often happens that the northern polarity never reaches thus far, but stops at a nearer point; and in that case, we generally find a weaker south pole appearing at some greater distance; and this pole also travels slowly onwards till it attains its furthest limit. This is often succeeded by another north pole, and even a greater number of alternations will sometimes take place; each successive pole, however, becoming weaker and more diffused in proportion as they are more numerous and more distant. The points where the polarities thus change from the one kind to the other have been called *consecutive points*. It is evident that alternations of this kind must very much disturb the regularity of the magnetic actions of bars in which they exist, and complicate the resulting phenomena.

It would appear, from a variety of facts hereafter to be detailed, that a certain time is in all cases required for the complete operation of magnetic induction.

(44.) There are certain circumstances and modes of treatment which tend to quicken the progress of this induction. The first of these is concussion. Whatever excites a tremulous or vibratory motion among the particles of the steel, promotes the transmission of

the magnetic polarities, and favours the induction of magnetism. Striking on the bar with a hammer is found to produce this effect in a remarkable degree; and the more so if it occasion a ringing sound in the steel, which is an indication that its particles are very generally thrown into vibratory motion. But any other cause producing agitation among the particles assists in the induction of magnetism.

(45.) The transmission of an electric discharge through a steel bar under the influence of a magnet, is sufficient to produce permanent magnetism. That the electricity acts here only by its mechanical operation, is proved by the effect being the same, whatever be the direction in which it is transmitted; that is, whether the positive stream of electricity be made to pass from right to left, or from left to right, along any part of the steel bar; or whether it be passed longitudinally or transversely through it. This mechanical operation of electricity is, however, to be carefully distinguished from an influence of a totally different description, which it is capable of exerting in producing magnetism, and the operation of which will be the subject of a distinct treatise hereafter to be published.

(46.) Heat also appears to act by removing the obstructions to the transmission of magnetism which exist in steel, in its ordinary state, and by thus reducing it nearly to the condition of soft iron. Accordingly, if a steel bar be heated, and placed in circumstances favourable to magnetic induction, if it be placed, for example, in the immediate vicinity of a magnet, and then suddenly cooled, it will be found, on its removal from the magnet, to have become strongly and permanently magnetic. The greatest degree of magnetism is produced by heating the steel to redness, and, while it is under the influence of a strong magnet, quenching it suddenly with cold water.

(47.) It will readily be understood that since the magnetism of a steel bar remains permanent, only because the peculiar texture of the steel presents an insuperable obstacle to its resuming its natural state of uniform distribution, all the causes which diminish this obstructing force, will give occasion to the escape of portions of this imprisoned magnetism, and will make the bar approach nearer to a neutral condition. In other words, its magnetism will be impaired and weakened, by the very same causes which favoured its acquisition when under the inductive process. It is accordingly found that any mechanical concussion, or any rough usage, has a tendency to destroy the power of a steel magnet. Dr. Gilbert, who was one of the earliest discoverers in this science, found that a magnet which he had impregnated very strongly was very much impaired by a single fall on the floor: and it has been observed since his time, that a magnet is more injured by falling on a stone pavement, or receiving blows which cause it to sound or ring, than by being struck with any soft or yielding substance.

(48.) In like manner the application of heat to a magnet is invariably attended by a dissipation of its magnetic power. It is even sensibly affected by the heat of boiling water; and a red heat totally destroys its magnetism. It has been observed by Mr. Canton, that if the temperature of the magnet has been raised only to that of boiling water, although it loses much of its power during the operation, yet that a great part of it is again recovered on its becoming cool. But after it has been heated to redness, no part of its magnetism is recovered on cooling.

(49.) The precise nature of the influence which heat has upon magnetism is far from being clearly understood; and there appears to be much discordance in the accounts given by different authors on this subject. This appears to have arisen in a great measure from a want of attention to the circumstance that the operation of heat is of two kinds: for while, on the one hand, it facilitates the induction of magnetism, on the other it weakens magnetic action. In those cases where the effects depend upon the readiness with which a piece of iron receives magnetism by induction, heat will favour this process; thus, soft iron is more disposed to be attracted by a magnet when hot than when cold, provided the heat be not excessive. But in as far as relates to permanent magnetism, the action of heat is to impair or destroy it; so that steel, when heated, is less capable of retaining its power than it is when cold. This happens in consequence of its being brought nearer to the condition of soft iron, by the separation of its particles. By raising the temperature sufficiently high, to a red heat for instance, the whole of its permanent magnetism is at once de-

stroyed, though it will still be susceptible, while in that state, of receiving temporary magnetism by induction, and therefore of being attracted by another magnet.

(50.) The direct tendency of heat to diminish magnetic power must also be taken into account in our estimate of the preceding phenomena. It not only promotes the destruction of permanent magnetism, but diminishes likewise the effects of that which is of a temporary nature. The degree in which heat possesses this direct influence, can be estimated only under circumstances in which no permanent change has been produced in the magnetism of a bar subjected to the change of temperature; that is, provided we find on the return of the bar to its former temperature, that it has retained all the power it had before the experiment. The limit beyond which no proper distinction can be accurately drawn between the effects of this twofold operation of heat, appears, according to the experiments of Mr. Christie, to be below 100° of Fahrenheit. From this temperature downwards the power of a magnet increases as it becomes colder; and this augmentation proceeds as far as the lowest temperature that has been tried.

(51.) The following are the results of an extensive series of experiments upon this subject made by Mr. Christie*. Commencing with a temperature of −3° of Fahrenheit, up to one of 127°, the intensity of magnetic power decreased as the temperature of the magnets increased. From an experiment he made at the Royal Institution, in conjunction with Mr. Faraday, in which a small magnet, enveloped in lint, well moistened with sulphuret of carbon, was placed on the edges of a basin containing sulphuric acid, under the receiver of an air-pump, he found that the intensity of the magnet increased to the lowest point to which the temperature could be reduced, and that the intensity decreased on the admission of air into the receiver, and consequent increase of temperature. This, he observes, is in direct contradiction to the notion which has been entertained of intense cold destroying the magnetism of the needle. Captain Middleton had announced† his having frequently observed that a compass appeared to be deprived of all magnetic power from cold, while he was navigating among the ice in Hudson's Bay; but recovered its power when brought into the cabin and warmed by the fire: and that this repeatedly occurred. There can be no doubt that this must have been owing to some other cause than the one he assigned.

With a certain increment of temperature, the decrement of intensity is not constant at all temperatures, but increases as the temperature increases. From a temperature of about 80° the intensity decreases very rapidly as the temperature increases, and beyond the temperature of 100°, a portion of the power of the magnet is permanently destroyed.

(52.) The effects produced on unmagnetized iron, by changes of temperature, were observed by Mr. Christie to be directly the reverse of those produced on a magnet; an increase of temperature causing an increase in the magnetic power of the iron, the limits between which, he observed to be 50° and 100°. This is in perfect conformity with the views we have above explained, of the nature of the operation of heat with regard to magnetism.

(53.) Although the direct tendency of heat to diminish magnetic power may, in a red hot bar, be not sufficient to prevent its receiving induced magnetism, yet when the temperature is still further raised, even this capability is destroyed; and accordingly we find that, at a white heat, iron appears to be totally insusceptible of any magnetic action. There are still, however, some curious anomalies occurring in the magnetic action of iron at these very high temperatures, of which further investigation alone can furnish the explanation.

(54.) In the account we have now given of the properties of iron and of steel, with regard to their capabilities of acquiring and of retaining magnetism, we have all along referred to those of pure metallic iron in its softest and most ductile state, and to those of steel which has been brought to its greatest degree of hardness by immersion in cold water after being heated; for it is in these two states that they exhibit the strongest contrast in these respects. We often, however, meet with this metal in states possessing intermediate degrees of the above qualities; that is, acquiring magnetism with less facility than soft iron, and retaining less of it than hard steel. It may be laid down as a general propo-

* Philosophical Transactions for 1825, p. 62.
† Philosophical Trans for 1738, vol. xl. p. 310.

sition, liable however to some exceptions, that the power of retaining magnetism in any specimens of iron or steel, is in proportion to its hardness.

(55.) But some of the combinations of iron with other substances affect its capacity for magnetism, independently of the hardness of the compound. A slight degree of oxidation pervading the mass of iron appears to increase its power of retaining magnetism; but a greater degree renders it totally insusceptible of being affected by the magnet, or of possessing any magnetic properties whatsoever. Combinations with phosphorus, with arsenic, or with tin, were found by Mr. Gay Lussac to produce compounds somewhat resembling those of carburet of iron or steel in their capability of retaining magnetism. Every thing depends, however, upon the proportions in which these several substances are united with the iron; for if they exceed a certain quantity, they totally incapacitate the compound from acquiring any magnetic properties.

(56.) It is only the finest and purest soft iron, free from all knots and veins, that returns to the state of perfect neutrality after it is removed from all extraneous magnetic influence. Iron is seldom found in this perfectly pure state; but even the purest iron may be rendered capable of permanently retaining magnetism, if it has been twisted or hammered violently. The slight superficial oxidation it undergoes by the action of the atmosphere, will also make it susceptible of some degree of fixed magnetism. But in its common state, iron may, on the whole, be regarded as incapable of any long retention of the magnetism which it may have received by induction.

(57.) It would appear from the experiments of Mr. Scoresby*, that the texture of all iron, even the most malleable, presents a certain degree of resistance to the transmission of magnetic power; for if a bar of iron be placed in circumstances favourable to its acquiring magnetism by induction, it does not acquire it in the degree of intensity of which it would be capable, were there no such internal obstructions to the transmission. If, under these circumstances, it be subjected to percussion, which, as we have seen, favours the transfer of magnetism in obedience to the attractive and repulsive forces that act upon it, it is found to acquire a much higher intensity of magnetic power than it would have received without such percussion. Nor is the whole of this power lost on the removal of the inducting cause; a part is retained by the iron, the internal structure of which appears to have undergone some alteration by the percussion.

As connected with this subject, we may notice the following curious observation of the same experimentalist*. Bars which had been strongly magnetized, and had their magnetisms destroyed or neutralized, either by hammering, heating, or by the simultaneous contact of the two poles of another magnet placed transversely, were always found by him to have a much greater facility for receiving polarity in the same direction as before, than in the contrary direction. Hence, it generally happened in his experiments, that one blow with the original north end downward, produced as much effect as two or three blows did with the original south end downwards. He also observed, that the polarity of *pokers*, generally supposed to be permanent, and considerable in intensity, was rather transient and weak; for in no instance did he meet with a poker the magnetism of which he could not destroy by a blow or two with a hammer on the point; and in general, two blows, even when the poker was held in the hand, and not rested upon any thing, were sufficient to invert the poles.

(58.) Soft steel is not much more retentive of magnetism than iron in its ordinary state. It is only when hardened that its magnetic powers become in any degree sensible. Dr. Robison states, that when steel is tempered to that degree which fits it for watch springs, it may acquire a strong magnetism, which it exhibits immediately on the removal of the magnet. But it dissipates very rapidly; and in a very few minutes it is reduced to less than one half of the intensity it manifested while in contact with the magnet, and to less than two-thirds of what it was immediately on removal from it. It continues to dissipate for some days, though the bar be kept with care; but the dissipation diminishes fast, and it retains at least one-third of its greatest power for any length of time, unless carelessly kept or injudiciously treated.

(59.) Steel tempered for cutting-tools

* Transactions of the Royal Society of Edinburgh, vol. ix. p. 253.

* Philosophical Transactions for 1822, p. 251.

(the same author observes), such as chisels, punches, and drills for metal, acquires magnetism still more slowly by induction, and receives less of it while in contact with the magnet; but it is less disposed to lose it, and finally retains a larger portion of what it had acquired. Steel made as hard as possible is still longer in acquiring all the magnetism which simple juxtaposition can give to it. It acquires less than the former; but ultimately retains a much greater proportion. The loadstone, or native ore of iron, resembles very hard steel in these respects; that is, in the time necessary for its greatest impregnation, and in the durability of the acquired magnetism.

(60.) We have seen that iron, or any of its compounds, when free from magnetism, is attracted by a magnet only in consequence of the induction of magnetism upon it by the magnet which attracts it. It follows, therefore, that the degree of susceptibility to induction may be accurately measured by the attraction which results from this property. With this view Mr. Barlow made a series of experiments to ascertain the relative attraction which different species of iron and steel had for the magnet; and obtained the following specific results, the relative magnetic power of each substance being expressed by numbers*.

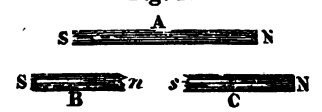
Malleable iron	100
Soft cast steel.....	74
Soft blistered steel ..	67
Soft shear steel.....	66
Hard blistered steel..	53
Soft shear steel.....	53
Hard cast steel.....	49
Cast-iron.....	48

§ 7. *Fracture*

(61.) We have hitherto been able to trace a very close analogy between the phenomena of magnetism and electricity, as far at least as relates to the law of action, and the influence of induction; but in pursuing it beyond this point it fails us entirely. Electricity, whether positive or negative, is not only capable of being excited by induction, but may be actually transferred from one body to another; but the transference of the magnetic polarities is a phenomenon which was never, in a single instance, known to take place. A body may, without difficulty, be rendered positively or negatively electrified; that is, it may be charged with a redundance of one or other of the two kinds of electricity; and the influence or agency, call it by what name we please, that has been gained by one body, is the same as that whic. has been lost by the other. It is not so with magnetism. There is never any transfer of properties, but only the excitation of those which were already inherent in the body operated upon. We always find in the same magnet, that the intensities of the two polarities, although each may occupy different portions of it, or be concentrated in some points, and diffused over others, yet still on the whole exactly compensate each other. We never can obtain a portion of iron or steel endowed wholly with either the northern or the southern polarity. Each appears to be strictly confined within the boundary of the surface of the body which contains it.

(62.) When a conductor of electricity, of an oblong shape, is placed near an electrified body, but not sufficiently near to receive any part of its electricity, it becomes electric by induction, the two ends of the body having opposite electricities. If, under these circumstances, the conductor be divided across the middle, and the two portions removed to a distance from one another, we obtain the two electricities separate; each portion retaining the electricity that had been induced upon it. The condition of a magnet appears to be exactly analogous to this in reference to the distribution of magnetic power; for the northern polarity appears to be collected in one half of its length, and the southern polarity in the other; and each of these agencies seems, indeed, to be almost entirely concentrated in the very extremities of the bar. What, then, ought to happen conformably with this analogy, were we to break a magnet (A, *fig.* 25,)

Fig. 25



across its middle? Might we not expect by this means to obtain the two polarities separate, each still contained in the same portions where they had before resided?

(63.) The result of this experiment is exceedingly curious, and what certainly

* Philosophical Transactions for 1822, p. 117.

no previous reasoning could have led us to anticipate. Each portion, B C, of the fractured magnet is at once converted into a magnet, perfect in itself; that is, each respectively has a north pole at one end, and a south pole at the other. That end of the magnet which, previously to the fracture, was a north pole N, continues to be a north pole, while the other end of that fragment *s*, that is, the broken end, becomes a south pole. The converse is true of that fragment B which originally contained the south pole of the magnet. It thus appears that the two fractured surfaces *n* and *s*, are now converted, the one into a north, and the other into a south pole, although that part had, in the original magnet, been apparently in a neutral state.

(64.) Similar consequences ensue from the subdivision of one of these fragments into any number of portions, however great; each lesser fragment constituting in itself a complete magnet furnished with its two poles.

(65.) It is observed by Æpinus, who made many experiments on the effects of the fracture of magnets, and the observation has been confirmed by others, that the neutral point in each fragment of the broken magnet is at first much nearer to the place of their former union than to their other ends. He states that in the space of a quarter of an hour after the separation, the neutral points advance nearer to the middle of each, and continue to do so, by small steps, for some hours, and sometimes days, and finally become stationary at the centre.

When a magnet is split according to its length, the two portions will have sometimes contrary, and sometimes the same poles as they had when they formed one piece. When one portion is much thinner than the other, the slender fragment generally has its poles reversed*.

Chapter II.

Laws of Magnetic Forces.

§ 1. *Relation of Intensity to Distance.*

(66.) It would be inconsistent with the elementary views to which we are at present confining ourselves, to engage in the investigation of the mathematical law which regulates the variations of intensity of the magnetic forces, both attractive and repulsive, at different distances. We shall here only observe that this law has been made the subject of diligent and careful inquiry by some of the most eminent philosophers of modern times; and shall content ourselves with merely stating the final result of their labours. It has been ascertained most satisfactorily that the same law of variation obtains in magnetic attractions and repulsions with relation to proximity, as in the electrical: namely, that the intensity of the force by which magnetic polarities act upon each other is inversely as the square of their distance. In this respect, therefore, they agree, not only with the electrical forces, but also with that of gravitation; and it would appear, indeed, to be a property common to all forces which emanate in every direction from a central agent.

(67.) The variations of the intensities of magnetic attractions and repulsions exerted between any two poles depend solely upon the distances at which they are placed; and are in no degree affected or interfered with by the interposition of other bodies which are not themselves magnetic. Numerous experiments have been made with a view of discovering whether there exists any substance which can modify or intercept the action of magnets when placed between them and the body acted upon; but the result has been uniformly the same: namely, that the intervening bodies, of whatever kind they were, provided they were not susceptible of magnetism, occasioned no difference in the observed effects.

This subject, however, involves a question, hereafter to be discussed, as to the magnetic susceptibilities of substances which are not of a ferruginous nature.

§ 2. *Mutual Action of Two Magnets.*

(68.) The general law of magnetic force with relation to distance being once established, it becomes interesting to follow its consequences and applications under a variety of circumstances. These consequences are always, even in the simplest cases, more complicated than electrical arrangements; because in magnets the two polarities are always conjoined, and their influence is never perfectly isolated. In studying the mutual actions between two magnets, or even between one magnet and the smallest conceivable piece of iron, we have always four polarities in activity, the two residing in one body, and the two residing in the other; these polarities are

* Derham, Philosophical Transactions, vol. xxiv. p. 2138.

not strictly confined to particular points in the magnet: for although much concentrated at the two ends, they exist with less intensity in other parts of the magnet.

(69.) Let us, however, suppose, for the sake of simplification, that the magnetic forces emanate solely from the two poles at the extremities of the magnet M, *fig.* 26, with its axis placed horizontally, while a smaller magnet B suspended on a point, or in other words, the needle of a mariner's compass, and which we shall therefore designate as *the needle*, is presented to it in the vicinity of its north pole, N, and with its centre in a line with the axis of the magnet. The north pole of the magnet attracts the south pole of the needle, and tends to turn it in the direction indicated by the arrow at *s*. It also repels the north pole of the needle, turning it in the direction indicated by the arrow at *n*. These two actions, it will be seen, both conspire to give the needle a rotatory motion in the same direction with regard to its centre, and to bring it into the position represented in the next figure, (27,)

Fig. 26.

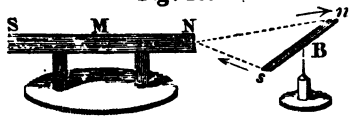
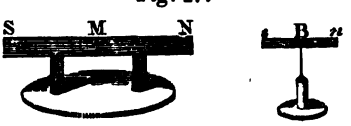


Fig. 27.



in which the south pole of the needle is turned directly towards the north pole of the magnet.

The influence of the south pole, S, of the magnet operates in a manner exactly contrary to that of its north pole; but being at a greater distance, its intensity is less; and all that it can effect is to subtract somewhat from the forces with which the needle would have been impelled, if the north pole of the magnet had acted alone. The general result as to the rotatory motion, is therefore determined by the predominance of the actions of the north pole of the magnet, and remains as before stated.

(70.) The tendency in one magnet to assume a particular position with relation to another magnet, is termed its *directive force* *. It results, as we have seen, from the conjoined influence of two forces, the one acting on the north, and the other on the south pole, and is therefore equal to the sum of these forces.

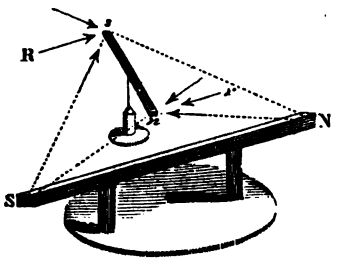
(71.) If we now consider what tendency the needle has to approach to, or recede from the magnet, we shall find the same forces, which in the former instance conspired together, now opposing each other. It is, in the first place, evident that while the needle is in the position shewn in *fig.* 26, that is, at right angles to the magnet, the attraction of the adjoining north pole of the magnet for the south pole of the needle, is balanced by its repulsion for its north pole; and the needle, although strongly urged by these forces to turn round its centre, has no tendency, on the whole, to recede from, or approach the magnet. When, however, it arrives at the position shewn in *fig.* 27, its south pole *s* being nearer to N than its north pole *n*, the attractive action is more powerful than the repulsion, and the needle is, consequently, now impelled towards the magnet. But the force which thus impels it results from the difference only of two contrary forces, the one attractive, the other repulsive.

(72.) Hence we may conclude that the directive force, which consists of the sum of two forces, is in all cases considerably greater than the attractive force exerted upon the whole needle; this latter force being only equal to the difference between the same forces. The ratio between the directive and attractive forces will be increased, either by diminishing the length of the needle, or increasing that of the magnet. Hence the polarity of a small needle may be considerable, while its attraction is quite insensible.

(73.) Let us next transfer the needle to the situation shown in *figs.* 28 and 29, in which its centre is in a line drawn from the centre of the magnet, and at right angles to its axis; the needle being supposed, as in the former case, to be so balanced as to turn freely in a plane which passes through the centre of the needle, and both poles of the magnet. Let it be placed in the position indicated in *fig.* 28, with one of its poles directed towards the middle of the magnet. The directive force is here compounded of four forces: the attractions of N for *s* and of S for *n*; and

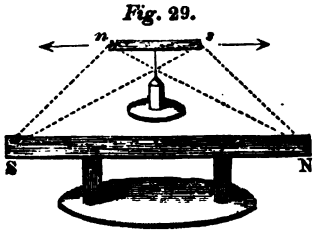
* Dr. Gilbert expressed it by the term *verticity*.

Fig. 28.



the repulsions of N for *n*, and of S for *s*. They respectively impel the poles *n s* of the needle in the directions denoted by the small arrows parallel to the lines in which these forces act. Those which act upon the remote pole of the needle *s*, compose a resultant having the direction of the upper horizontal arrow R, at right angles to the length of the needle, which is also the radius of its revolution. Those forces which act upon the opposite pole *n*, compose another resultant force in the opposite direction, expressed by the lower horizontal arrow *r*. Now these two resultant forces having opposite directions, and acting at the opposite ends of the needle which turns upon its centre, conspire in producing a rotation in the same direction with relation to that centre; and will tend to bring the needle into the position shown in *fig.* 29, in

Fig. 29.



which its direction is parallel to that of the magnet, but in which its poles are reversed when compared with those of the magnet; that is, the north pole of the needle being on the side of the south pole of the magnet, and its south pole on the side of the north pole of the magnet. This relative situation has been called by some authors *the subcontrary position.*

(74.) Here also it may be remarked, that in consequence of the greater proximity of the poles of the different denominations, compared with that of the poles of the same name, the sum of the attractive forces exceeds that of the repulsive; the former will therefore prevail, and the needle will have a tendency to move towards the magnet in the direction of the line connecting their centres.

(75.) A similar process of reasoning, derived from the same principles, will enable us to determine the resultants of the forces which act upon the needle when its centre is situated in different directions relatively to the axis of the magnet: and consequently what will be its movements, and what its final position of equilibrium. In oblique positions, indeed, the process of investigation becomes more complicated, for it is necessary to take into consideration the different intensities of each of the four forces concerned, with reference not only to the respective distances of the poles of the needle from those of the magnet, but also to their respective directions in the plane of rotation.

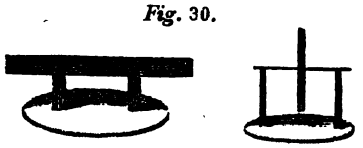
(76.) If the plane of rotation, to which the movements of the needle is limited, be one which does not pass through the poles of the magnet, the complication of the problem becomes still greater. There are, however, three general results at which we may arrive, which tend very much to simplify the resolution of questions relating to this subject.

(77.) The first is, that if we suppose the needle to be at perfect liberty to move on its centre in all directions, the position of equilibrium at which it will arrive by the conjoint action of all the forces which impel it, will always be situated in the plane which includes the poles of the magnet and the centre of the needle. This plane may be called, for the sake of distinctness, *the magnetic plane;* and the position assumed by the needle in this plane may be called its *magnetic* position.

(78.) Secondly, when the movements of the needle are limited to any particular plane, its position of equilibrium is that which makes the nearest approach to the magnetic position that the case will admit of. It will therefore be situated in a plane passing through the magnetic position, and at right angles to the plane of revolution.

(79.) Thirdly, if the plane of revolution be perpendicular to the magnetic position, the needle will be in a state of equilibrium with regard to the forces exerted upon it by the magnet, in all positions. Such a plane may be called *the plane of neutrality.* An example of this is shown in *fig.* 30, where the needle,

Fig. 30.



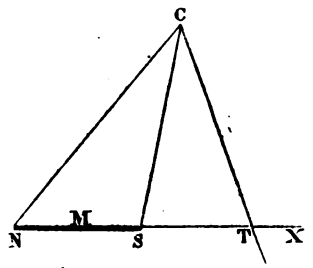
turning on a horizontal axis in a line with the magnet, is limited in its motion to a vertical plane perpendicular to its position of equilibrium. In this case it will have no tendency to assume any one position in preference to another, in this plane.

§ 3. *Magnetic Curves.*

(80.) In order still further to generalize our views, let us conceive the needle to be exceedingly short when compared with the length and distance of the magnet; and we shall then arrive at still more simple conclusions with regard to its positions of equilibrium in the magnetic plane. The two poles of the needle may, with regard to the action of the magnet, be considered as coincident; the intensities of the actions of any one of the poles of the magnet upon them are so nearly equal that their differences may be regarded as infinitely small. The attraction of the magnet for this minute needle, an attraction which, as we have seen, depends upon their difference, must accordingly be inappreciable. But the directive force, on the contrary, depending on the sum of these actions, must be very effective; and it is to the operations of the latter of these forces only that we need direct our inquiries.

(81.) The problem to be solved is this: given the position of the magnet M, (*fig.* 31,) and of its two poles N and S,

Fig. 31.

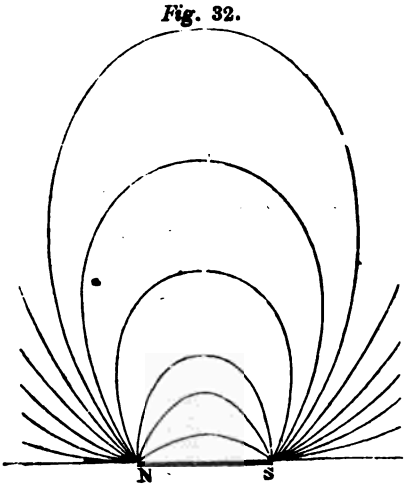


and also the place of the centre C of the needle, which is supposed to be at liberty to revolve only in the magnetic plane, to find the direction C T, at which the rotatory force resulting from the action of the north pole N of the magnet on the two poles of the needle in the direction C N, exactly balances that resulting from the action of the south pole S of the magnet on these poles, in the direction C S, each force having an intensity reciprocally proportional to the squares of these respective lines.

It may be mathematically demonstrated * that if such be the law of the magnetic forces, the direction of the needle is that of the tangent of a peculiar curve of an oval shape, which has been denominated the *magnetic curve*. Every magnet having two poles N and S (*fig.* 32) has a system of mag-

* Demonstrations of this and of the other fundamental properties of the magnetic curves are given in the Journal of the Royal Institution, for Feb. 1831, by the author of this Treatise.

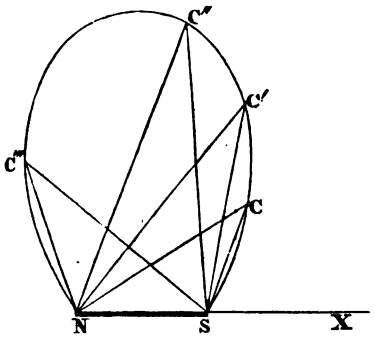
Fig. 32.



netic curves related to the line joining these poles, and which may be called its axis. The general form and disposition of these curves, according to their different distances from the magnet, is shown in the figure.

(82.) The magnetic curves have the following remarkable property; namely, that the difference of the cosines of the angles, which lines, drawn from any point in the curve to the two poles, make with the axis, taken on the same side, is constant. Thus, in the curve S C C′ C″ N, *fig.* 33, the sum of the

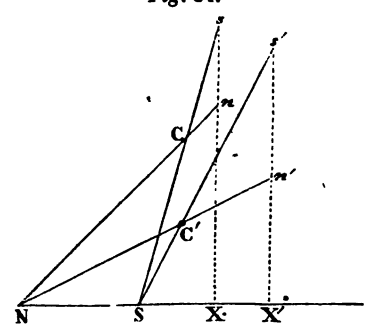
Fig. 33



cosines of the angles C N X and C S X, is equal to the sum of the cosines of the angles C′ N X and C′ S X. When, however, the angle C″ S X exceeds a right angle, its cosine being negative, it will be the sum (instead of the difference) of the cosines of the polar angles C″ N S, C″ S N, that is constant. When the angle C‴ N X is also obtuse, both the cosines being negative, it is again their difference that is constant.

(83.) If two radii of equal length, N *n*, S *s*, *fig.* 34, be made to revolve in the same

Fig. 34.



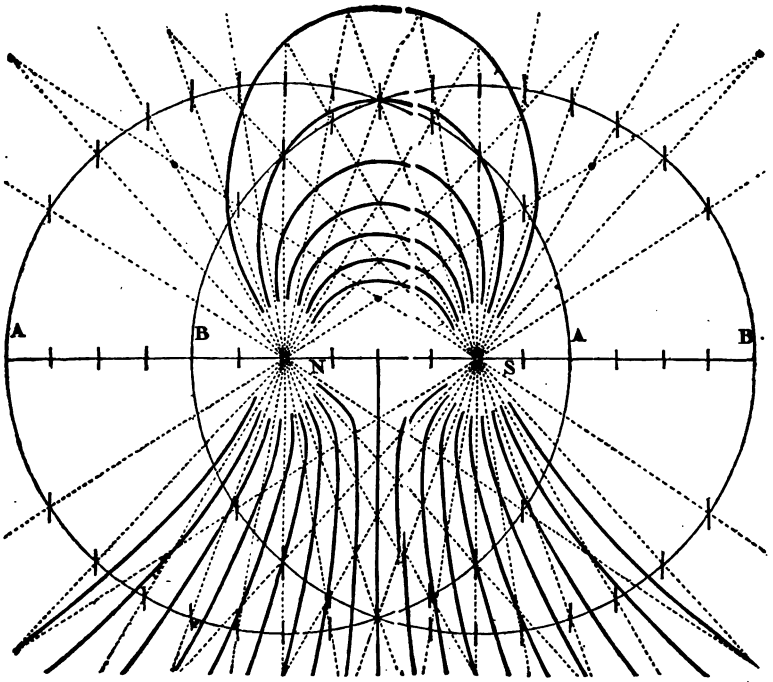
direction round their respective centres N and S, while their other extremities, *n* and *s*, are kept continually in such a relative position as that a line drawn through them shall always be perpendicular to the axis N X, then the line, constituted by the successive points of intersection C, C′ of the radii, will be a magnetic curve *.

(84.) The most expeditious method of delineating a great number of magnetic curves related to the same base, in order to obtain a general view of the entire system of these curves, is to describe from each pole, N, S (*fig.* 35), as a centre, the equal circles or semi-circles, A A, B B, with as large a radius as the paper will conveniently admit of; and, dividing the axis, produced till it meets both circles, into any number of equal parts, to mark off, on the circumferences of both the circles, the points where they are cut by perpendiculars from these points of division; then, drawing radii from the centre of each circle to the divisions of its respective circumference, the mutual intersections of these radii will form different series of points indicating the course of the magnetic curves which pass through them. In the present case these curves are composed of a succession of diagonals of the lozenge-shaped interstices formed by the intersecting radii, as is shown in the upper half of *fig.* 35.

(85.) The forms and disposition of these curves are elegantly illustrated by the lines in which iron-filings arrange themselves when acted upon by a powerful magnet. In order to exhibit them, we need only place a sheet of paper or pasteboard immediately over a straight magnetic bar laid flat upon a table, and scatter lightly some very fine iron-filings over the pasteboard; which is best done by shaking them through a gauze bag. If we then tap gently upon the paper, so as to throw them into a slight agitation, they will arrange themselves with great regularity in lines, which exactly follow the course of the magnetic curves, extending from one pole of the magnet to the other. These minute fragments of iron, being rendered magnetic by induction, have their dissimilar poles fronting each other, and therefore attract one another, and adhere together

* The author of this Treatise has constructed a system of rulers by which magnetic curves may be mechanically delineated, founded on the principle stated in the text. The description of this instrument is contained in the paper above referred to in the Journal of the Royal Institution.

Fig. 35.



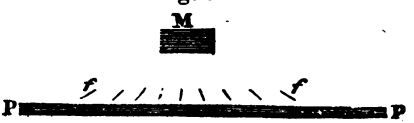
in the direction of their polarities, which is that of the tangent to the magnetic curve: thus affording a beautiful ocular exemplification of the mathematical properties of these curves.

(86.) By continuing to tap upon the paper, the filings arrange themselves still more visibly into separate lines; but here a curious, and perhaps unlooked for phenomenon presents itself. The lines gradually move and recede from the magnet, appearing as if they were repelled, instead of attracted, as theory would lead us to expect. This arises from the circumstance that each particle of iron, or cluster of particles, is thrown up into the air by the shaking of the paper, and, while unsupported, immediately turns on its centre, and acquires a position more or less oblique to the plane of the paper. This is shown in *fig.* 36, in which M represents a section of the magnet, P P a section of the paper, and *ff* the position of the filaments of iron thrown up into the air. The end of each filament nearest to the magnet is thus turned a little downwards, and the filament falls upon the paper at a point a little more distant than that which it before occupied; and thus, step by step, it moves further and further from the magnet, till it reaches the edge of the paper and falls off.

(87.) When the magnet, instead of being beneath the paper, is held above it, the effect is just the reverse. In this latter case, the lower ends of the filaments having a tendency to turn towards the magnet, the filings gradually collect under it, when made to dance by the vibrations of the paper, instead of falling outwards as they did before. This will be rendered apparent by *fig.* 37, where the letters indicate the same objects as in the preceding figure.

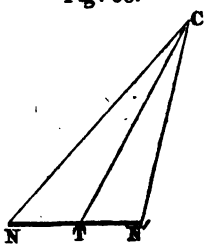
Fig. 36.

Fig. 37.



(88.) Magnetic curves of a different kind are constituted by the balanced actions of two poles of the same denomination placed near to each other. When, for instance, a second north pole N′ (*fig.* 38) is substituted, instead of the south pole S, both poles will act in a similar manner, and in directions not very different.

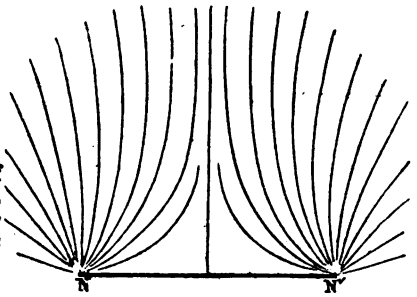
Fig. 38.



In order to render the conditions of this case as simple as those of the last, we must suppose that the action of the south poles belonging to the two north poles N, N′, whose action we are examining, is, from their remoteness, too feeble to influence the results. In the former case, where the actions of the two poles were of a contrary kind, the resultant of their joint action, or the line C T (*fig.* 31) passed in a direction intermediate between N C prolonged and C S, and therefore cut the axis N X at some point in the prolongation of N S. But in the present case, the two magnetic poles being of the same kind, their action is similar, and their resultant is a force of which the direction is intermediate to the lines C N and C S; and this line produced must cut the axis somewhere between N and N′. In consequence of this change of position, which produces a change in the sign of the cosine of the angle C S T, which is now C N′ T, the relation of the cosines of the polar angles is as follows; namely, that the sum (and not, as before, the difference) of the cosines of the angles which lines, drawn from any point in the curve to the two poles, make with the axis, taken on the same side, is constant. This applies to the case in which the angle formed by C N′ with the produced axis is acute, and its cosine positive. When it is obtuse (or C N′ N acute), the cosine becoming negative, it is their difference which is constant.

(89.) The intersections of the radii, drawn according to the method above described, § 82, will also point out the course of those curves which belong to the case where the acting poles are similar. For this purpose they must be taken in a different order of arrangement, and followed in the lines of the other diagonals of the lozenge-shaped intervals between the intersecting radii; that is, of the diagonals which cross those constituting the curves in the former case, as is shown in the lower half of *fig.* 34. These *divergent* curves, as they have been called in contradistinction to the former or *convergent* ones, are delineated in *fig.* 39; and may, in like manner, be exhibited by the arrangements of iron-filings round two similar poles.

Fig. 39.



(90.) When the actions of the four poles of two magnets are taken into account, the magnetic curves expressive of the direction of a needle influenced by them, become, of course, much more complicated.

Chapter III.

Terrestrial Magnetism.

§ 1. *Variation of the Compass.*

(91.) It has been already stated (§ 6), that if a magnetic bar be poised on its centre so as to move freely in a horizontal plane, and if no ferruginous body be sufficiently near to affect it sensibly, it will assume, when left at liberty, a direction nearly north and south. When disturbed from this situation, it returns, after several oscillations, to the same position. On this property is founded the mariner's compass, which is of such essential use in navigation. In moving horizontally towards the position which it thus tends to assume, the needle of the compass is said to *traverse*.

(92.) It is found that in this country, as well as throughout Europe, the north pole of the compass deviates a certain number of degrees to the westward of the exact northern direction. This deviation from the true geographical meridian has been called the magnetic

declination; but it is more usually known by the term *Variation of the Compass.* The vertical plane which passes through the direction of the horizontal needle at any particular place is termed the *magnetic meridian* of that place, in contra distinction to the *geographical* or *true meridian,* which is a vertical plane passing through the poles of the earth.

(93.) There are but few places on the earth where the compass points directly to the poles; that is, where it exhibits no variation. As far as observation has extended, these places are situated in a line which encompasses the globe, and is called *the line of no variation.* In many of its portions it appears to form part of a great circle of the sphere, but in others it deviates much from regularity, presenting many flexures in its course. It may be considered as commencing from a point which may be designated as the principal arctic magnetic pole of the earth, and the exact situation of which is not yet perfectly ascertained, although the late voyages of discovery in these regions have enabled us to form a tolerable approximation to the precise spot, which appears to be a point somewhere to the westward of Baffin's Bay. After crossing the United States of North America it passes along a tract of the Atlantic, a little to the eastward of the windward West India Islands, till it touches the north-eastern point of the South American continent. Thence it stretches across the Southern Atlantic towards the south pole, where navigators are unable to follow it. It re-appears in the eastern hemisphere to the south of Van Dieman's Land, and passing across the western part of the Australian continent, is again found in the Indian Archipelago. Here, according to Biot, it divides into two branches, one of which crosses the Indian Sea and enters Asia at Cape Comorin; it then traverses Hindostan and Persia, and passing through the western part of Siberia stretches over to Lapland and the Northern Sea. The second branch pursuing a more directly northern course, traverses China and Chinese Tartary, and makes its exit from Asia in the eastern division of Siberia, where we again lose it in the Arctic seas. Between these there must exist an intermediate line of no variation in some part of the continent of Asia; but the observations we possess regarding it are, as yet, too imperfect to admit of any attempt to trace it correctly.

(94.) If we consider these Asiatic lines of no variation as composing a single band, we may then consider the globe as divided by this and the corresponding American line into two hemispheres. In that hemisphere which comprehends Europe, Africa, and the western parts of Asia, together with the greater portion of the Atlantic, the variation is to the west. In the opposite hemisphere, which comprises nearly the whole of the American continents, both North and South, and the entire Pacific Ocean, together with a certain portion of Eastern Asia, the variation is to the east.

§ 2. *Dip of the Magnetic Needle.*

(95.) But in order to arrive at a knowledge of the real influence which the earth exerts on a magnetic needle, it is not sufficient to ascertain the position it assumes when its movements are confined to a horizontal plane, as it is in the mariner's compass of the ordinary construction: we must place it in such circumstances as will allow it to move freely in a vertical plane also. But to effect this in an unexceptionable manner is extremely difficult. The great obstacle with which we have to contend is the force of gravity, which by acting in one direction, interferes with the operation of the force of terrestrial magnetism, which acts in a different and in an oblique direction.

(96.) The readiest mode of removing the influence of gravity, is to affix a steel needle to a cork, or other buoyant substance, and to immerse it in water, adjusting the specific gravity of the two bodies, so that they may remain suspended in the middle of the fluid without any tendency either to float or to sink; taking care at the same time that the centre of gravity of the whole coincides with the centre of its figure, so that, when the needle is unmagnetic, and united to the cork, the two together, placed in any position in the fluid, shall have no tendency to take any other position. If the needle be now rendered magnetic, and replaced as before, it is found to assume a position nearly vertical, that is, making an angle with the plumb line of about 20 degrees, the north pole of the needle being turned about 25 degrees to the westward of the true north. Its deviation from the plane of the meridian is equal to the variation of the horizontal needle. Its inclination to the horizontal plane, or 70°, is called the dip. But this method, though well fitted for illustrating the general fact, and the principle on which it depends, is not

adapted for accurate measurement. For this purpose we must have recourse to other contrivances.

(97.) The magnetic force may, by the ordinary dynamic method of the resolution of forces, be resolved into two forces, the one acting vertically, the other horizontally. The latter of these forces, namely, the horizontal force, is the only one with the action of which gravitation does not interfere; and accordingly, the mariner's compass indicates by its motions, the effects of this part of the terrestrial magnetic force, and this only. In order to ascertain the vertical force, we must proceed in a different manner. The needle must be furnished with an axis, at right angles to its length, and adjusted very carefully, so that it may pass as exactly as possible through its centre of gravity. This, of course, can only be done when the needle is wholly free from magnetism, and secured, in the manner hereafter to be pointed out, from all magnetic influence which the earth might exert upon it. The axes should be supported horizontally in such a manner as to allow the needle complete freedom of motion in a vertical plane. The needle being thus balanced, will have no tendency to incline to one side rather than to another, and will remain at rest in any position in which it may happen to be left, as long as no extraneous force is applied to it. When this has been accomplished, the needle is to be magnetized, by the methods hereafter to be described, as strongly as possible, and it is then to be replaced on its supports, which are to be turned so that the plane in which the needle is allowed to move, may coincide with that of the magnetic meridian. It will be found that, in this situation, the end of the needle to which a northern polarity has been imparted, will preponderate, or *dip*, as it is called, and after a certain number of oscillations, will settle at a determinate point. The line which its axis assumes under these circumstances, is termed the *magnetical direction*, or *position*. The dip of the needle was first observed by Norman.

(98.) The inclination of the needle, or *dip*, like the variation, differs in different parts of the globe. The latest accurate observation of the dip in London, of which we have any record, is that of Captain Sabine, who ascertained it, in August, 1828, to be 69° 47′.* As a general rule, to which, however, there are many exceptions, the dip diminishes as we approach the equator, and increases as we recede from it on either side. Towards the polar regions it is very great, and as we come near to the poles, it approaches to a right angle. At the magnetic poles themselves, the dipping needle would, of course, be exactly perpendicular to the horizon. Those places on the earth where the needle is perfectly horizontal, that is, where there is no dip, are in a line that encircles the globe, and is termed the *magnetic equator*.

(99.) As the magnetic poles are not situated exactly at the poles of the earth's rotation, but at some little distance from them; so, the magnetic equator does not coincide with that of the earth; though it does not in any part deviate widely from it. In a general way we may consider it as a great circle of the globe inclined to the terrestrial equator at an angle of about 12 degrees; its intersections with it being situated at the longitudes 113° 14′ west, and 66° 46′ east from the meridian of Greenwich. Such, at least, is the result given by all the observations made for an extent of more than one half of its circuit, in the Atlantic and Indian Oceans, and that part of the Pacific which is nearest to the South American continent, as appears from a table of these observations given by Biot*. But a remarkable anomaly is met with when we trace the course of the magnetic equator across the Pacific Ocean. This line is found in the southern hemisphere in the American continent, and joins the equator as before-mentioned, at a longitude of about 113°; but still further to the westward, at longitude 156° 30′ it is again met with at a distance from the equator and to the south of it. In the Sea of China at 116° east longitude, it is found to the north of the equator, which it must therefore have crossed at some intermediate point; and it is again inflected towards the south, so as to traverse the equator at the eastern node already mentioned.

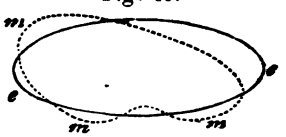
It appears, therefore, from these observations, that there are at least three points in the terrestrial equator where the magnetic equator coincides with it; and the probability is, that there are four: because, if the latter curve passes to the northern side of the equator at its western coincidence, it must again cross it before

* Philosophical Transactions for 1829. Since the above was written, we are informed that the dip has been ascertained by Capt. Segelcke to be 69° 38′ at Woolwich, in Nov. 1830.

* Traité de Physique, tome III. p. 130.

it can arrive at the southern situation in which it has been met with in longitude 156½°. These inflexions will, therefore, assume a figure, with relation to the terrestrial equator, somewhat like that represented in *fig.* 40, where the dotted line *m m m*, is the magnetic, and the continuous line, *e e*, the terrestrial equator.

Fig. 40.



§ 3. *Variations in the Intensity of Terrestrial Magnetism.*

(100.) Besides the variation and the dip, which together constitute the magnetic position, and which differ much in different situations, there is also a third circumstance highly deserving our attention in connexion with this subject, namely, the intensity of the force which directs the needle towards this position. Extensive observations of the relative intensities of the magnetic force of the earth in different parts of its surface, are of greater value in enabling us to understand the general system of terrestrial magnetism than those in the dip or variation. We know that this force varies greatly in different latitudes; but our information with regard to the exact amount of this variation is exceedingly scanty, both from its importance not having been felt, and the consequent omission of the proper observations with regard to it, and also from the greater difficulty there is in conducting the experiments which are required to ascertain it.

(101.) The best mode of estimating the comparative intensities of the magnetic action in the same needle in two different places, is to count the number of oscillations which it makes in a given time, a minute for example, on its being disturbed from its position of equilibrium, while it is resuming that position. The movements of the needle being regulated by the same dynamical laws which govern the oscillations of the pendulum, it is a necessary consequence of those laws, that the intensity of the force producing the oscillations, is proportional to the square of the number of oscillations performed in a given time. Mr. Graham appears to have been the first who devised this method of measuring the magnetic intensities.

(102.) The first accurate observations of this kind were those made by Humboldt, and by De Rossel: who have completely established the general fact, that the intensity of the force of terrestrial magnetism increases as we recede from the equator, where it is weakest, till we approach the poles: at the magnetic poles themselves, it is probably greater than at any other spot. We have every reason to expect that great light will be thrown on this department of the science from the labours of Professor Hansteen of Christiana, who is now travelling at the expense of the King of Sweden, and with the permission of the Emperor of Russia, for the purpose of observing the magnetic dip, variation, and intensity, over the whole of the North of Europe and of Asia. He has especially directed his attention to trace the course of the lines of equal intensity, or *isodynamic lines* as they have been called: that is, the lines connecting those places where a needle freely suspended in the magnetic direction, and drawn a certain number of degrees from this position, makes the same number of vibrations round the point of rest in an equal time.

§ 4. *Hypothesis of the Magnetism of the Earth.*

(103.) From a consideration of the general facts that have now been stated with respect to the influence of terrestrial magnetism, it will be sufficiently evident that the earth acts upon magnetised bodies in the same way as if it were itself a magnet; or rather as if it contained within itself a powerful magnet lying in a position nearly coinciding with its axis of rotation. This hypothesis was originally proposed by Dr. Gilbert in his work entitled "Physiologia nova de Magnete, et de Tellure magno magnete," published in the year 1600; and Kepler ranks this hypothesis among the greatest discoveries in the annals of science.

(104.) In order to make this hypothesis agree with facts, we must assume that that pole of the terrestrial magnet which is situated in the northern regions of the earth, attracts the north pole of the compass needle, and consequently that it has the same properties as the south pole of an ordinary magnet. The opposite pole of the earth, or that situated in the antarctic regions, has the contrary properties, for it attracts the south pole of the compass; and therefore cor

responds in its properties to the north pole of a common magnet.

(105.) It may be necessary to remark that this circumstance of the south pole of the terrestrial magnet being situated near the north pole of the earth, and *vice versa*, has occasionally created a confusion of terms. Some authors have taken a fancy to reverse the names we have hitherto given to the magnetic polarities: assuming that it is more correct to set out by calling that property which distinguishes the pole of the terrestrial magnet situated in the northern regions, the northern polarity: and consequently to give the name of the south pole to that pole of the compass, or ordinary magnet, which is attracted towards it, and which of course has the opposite polarity. For the same reason they would call the antarctic pole of the magnet of the earth *the south pole*, and that end of the needle which is turned towards it, *the north pole*. Mr. Savery * endeavoured to avoid this confusion of terms by using the word *end*, in contradistinction to that of *pole;* and this phraseology is adopted by Mr. Christie in his papers in the Philosophical Transactions, as appears from the following passage: "To prevent any ambiguity, I must here state, that by the *south pole* of a magnet, I understand always the end which, when the magnet is freely suspended, points towards the north pole of the earth; so that the *north end* is the *south pole*, and the *south end* the *north pole* of a magnetic needle." It matters little which set of terms are used, provided they are clearly defined, and all persons agree to abide by these definitions. But wherever a diversity of practice exists, it is then best to adhere to that which most generally prevails: in the present case the authorities in favour of the nomenclature we have adopted are much the most numerous.

(106.) Some have attempted to avoid the confusion which the changes just mentioned would lead to, by the introduction of the terms *Boreal* and *Austral* instead of *north* and *south:* the former set of terms having reference to the natural magnetism of the earth, the latter to that of the needle, or artificial magnet: that is, they would express what we have all along called the *northern polarity*, by the term *Austral polarity;* and the *southern polarity*, they would translate by the expression *Boreal polarity*. We should not have dwelt upon this comparatively unimportant topic, were it not that this change of language is sanctioned and adopted by Biot and most of the Continental writers on magnetism.

(107.) Assuming it, then, as an hypothesis, that the earth contains in its axis, or near it, a powerful magnet, let us note the consequences which follow from it, and compare them with the facts. We shall begin with those that relate to the inductive power of the earth's magnet: a power which will be exerted in the direction which a magnetised needle, at perfect liberty to move, would assume in consequence of the action of terrestrial magnetism; that is, in the direction of the magnetic position. In this part of the globe this position is, as we have seen, not very far from the perpendicular to the horizon. A bar of unmagnetised iron placed in the vertical position, or near it, ought therefore to become magnetic from the influence of the earth, and merely in consequence of its position. Its lower end should exhibit the properties of a north pole, and its upper end those of a south pole. All this agrees perfectly with experience. An iron bar held nearly upright will be found, at its upper end, to attract the north pole of a compass needle, and repel the south pole: it is, therefore, itself a south pole. Its lower end, on the contrary, will attract the south, and repel the north pole of the compass: and has therefore a northern polarity. That these properties of the ends of the bar depend altogether on the position of the bar itself, is proved by reversing its position; when the two ends will be found to have exchanged polarities merely by their change of situation: the upper end being always a south, and the lower end a north pole. On the other hand, if the bar be placed in a position at right angles to the magnetic position, (for example, horizontally, and with the ends directed to the east and west,) it will not exhibit any characteristic magnetism.

(108.) The magnetism which a soft bar of iron derives from its position with relation to the earth, is, as we have just seen, of a transitory kind; immediately lost on turning the bar so that it makes a right angle with the magnetic position; and again acquired, but with contrary poles, when its position is reversed. But this is not the case with harder bars, for, by remaining for a considerable time in a vertical position, they are found to ac-

* Phil. Trans. for 1730, p. 295.
† Ibid. for 1823, p. 344.

quire a sensible and permanent magnetism. This is generally the case with the stationary iron bars belonging to a building, and even with pokers and other fire-irons which have long been kept in an upright position. This circumstance will also readily account for the permanent magnetism of that class of iron ores to which the loadstone belongs. Indeed it is perhaps not going too far to assert with Professor Robison that all the magnetism which we observe, whether in nature or art, is either the immediate or the remote effect of the magnetism of the earth.

(109.) All the phenomena which we have already described as the consequences of induced magnetism proceeding from ordinary magnets, are exemplified also in the case of that derived from the magnetism of the earth. It is most readily induced, but soonest lost, in the softest kinds of iron and steel; it is slowly acquired, but more permanently retained in hard-tempered steel. Percussion promotes the change, of whatever kind it may be, which the position of the bar relatively to the earth has a tendency to produce. Hence we see the reason why the steel bar described in § 6 became permanently magnetical by being struck, while in a vertical position, with a hammer. Mr. Scoresby found that even a bar of soft iron, held in any position, except in the plane of the magnetic equator, may be rendered magnetical by a blow with a hammer or other hard substance; and both ends seem to acquire, by this treatment, an equal degree of magnetism.

On the other hand, an iron bar, possessing permanent polarity, when placed any where in a direction at right angles to the magnetic position, and struck several times, has its magnetism always much weakened, and may even be deprived of the whole of its magnetism by a single blow. This affords, indeed, an excellent method of depriving iron of its magnetism. Rough treatment of any kind, such as filing or scouring the surface of iron, and more especially bending or twisting it, when in the magnetical position, tends to impart to it the magnetism corresponding with that position; or to destroy its previous magnetism, if it be subjected to the same treatment in a position at right angles to this.

Iron heated to redness, and quenched in water, in a vertical position, was found by Mr. Scoresby to become magnetic; the upper end acquiring the southern, and the lower end the northern polarity. Hot iron, according to the same experimentalist, receives more magnetism of position than the same when cold. An iron bar is rendered magnetical by passing an electrical discharge through its axis, provided it be in a position favourable to induction by the earth: and the polarity it acquires corresponds with the effects of this induction. Electricity appears to act, in this instance, merely by its mechanical agency, and independently of a peculiar influence of another kind which it possesses, and which will be the subject of future inquiry.

(110.) Let us now examine how far Dr. Gilbert's hypothesis corresponds with the actual phenomena of the variations of magnetic position in different parts of the globe. For this purpose, it will be necessary to revert to what was explained in a former chapter regarding the positions which a small needle assumes when under the influence of a strong magnet in its vicinity, and variously situated with respect to it. These positions, we have seen, are tangents to a magnetic curve passing through the two poles of the great magnet, and through the centre of the needle. The direction of the tangent, which is the same as that of the dipping-needle, together with that of a vertical line, or one perpendicular to the horizon, will determine the plane of the magnetic meridian, for it is the plane which includes both these lines. The compass-needle, which turns in an horizontal plane only, will arrive at its position of equilibrium when it is situated in the plane of the magnetic meridian, because it then makes the nearest approach of which it is susceptible, to the position of the dipping-needle, which is that towards which the magnetic influence of the earth tends constantly to bring it.

(111.) In those parts of the globe where the dip is very small, the horizontal needle is capable of taking a position very nearly approaching to that of the dipping-needle: hence the terrestrial magnetism is exerted in bringing it to this position with very little loss of its force. This happens in the equatorial regions of the earth. In high latitudes, on the contrary, where the dip is great, the forces which actuate the horizontal needle, act more obliquely, and therefore to great disadvantage: hence the compass-needle is more feebly impelled; the point of rest is less decidedly marked,

and the compass traverses slowly. The absolute intensity of the terrestrial force is, indeed, greater in the latter case than in the former; but the increase is not sufficient to compensate for the greater obliquity of its action. If we could place ourselves exactly over the north or south magnetic pole of the earth, the dipping-needle would take a vertical position, and the horizontal compass would no longer be sensible to the influence of terrestrial magnetism, but would remain at rest in any position in which it might happen to be placed.

(112.) All these consequences of the hypothesis which ascribes terrestrial magnetism to the influence of a magnetic power in the central regions of the earth, and of which the direction nearly coincides with its axis of rotation, may be experimentally illustrated by placing a strong magnet in the centre of an artificial globe. The points on the surface which are opposite to the poles of the magnet, are to be marked as the terrestrial magnetic poles. A great circle being traced equidistant from these poles, will be the magnetic equator, dividing the globe into the northern and southern magnetic hemispheres. Great circles passing through the poles, and crossing the equator at right angles, will be magnetic meridians; of which the one which also passes through the poles of the earth's rotation will be the lines of no variation. Smaller circles parallel to the magnetic equator, will indicate situations when the dip is the same in all. The lines of equal variation will be curves of particular forms less easily determinable. The accordance of fact with theory may now be verified by placing in different situations, on the surface of a globe so prepared, a small needle suspended as freely as possible by a fine thread, which holds it balanced as nearly as possible at its centre of gravity, and observing the positions it assumes in each situation.

(113.) But when we come to compare the regular lines thus traced from theory, on the supposition of a single central magnet, with the lines which observation points out as those indicating the actual variations of the magnetism of the earth, we meet with very remarkable discordances. Many have been the attempts made to explain the irregularities and anomalies in the course of the magnetic lines by suppositions of various kinds. There is reason for believing that the northern and the southern magnetic poles do not occupy points on the globe diametrically opposite to each other, which would be the case if the magnetic influence emanated from the centre of the earth. It has been supposed, in consequence, that the terrestrial magnet, or centre of magnetic force, was eccentric. But this supposition alone will not suffice; for there are various indications of the influence of more than one pole in each hemisphere of the earth; and the probability is that these poles are of very unequal intensities. Other irregularities exist which appear to owe their existence to the influence of causes entirely local and of limited extent, such as might be supposed to be derived from large masses of iron situated at different depths beneath the surface of the earth.

(114.) The observations best calculated to decide the important question of the existence of secondary magnetic poles, appear to be those of the variations of magnetic intensity, from which we derive the knowledge of the isodynamic lines already adverted to (§ 102); for these lines will necessarily arrange themselves in regular order around the point or points in each hemisphere when the intensity is greatest, that is around each respective pole. If these poles were single, and placed opposite to each other in the globe, one in the northern and the other in the southern hemisphere, the lines of equal intensity would form parallel circles, analogous to those of geographic latitude. Captain Sabine remarks* that the observations on this subject, made previously to those of Professor Hansteen, appeared to corroborate such an hypothesis; for, although they extended widely over the magnetic parallels in the northern hemisphere, namely, from the least almost to the greatest intensity, yet they were confined, in respect to longitude, to a space little more than a quarter of a hemisphere; and to that quarter which is immediately opposite to the countries visited by Professor Hansteen. Within the space that had been thus examined, the isodynamic curves appeared to arrange themselves with comparative insignificant deviations, in parallel circles around a point situated in the north-eastern part of Hudson's Bay, and, as nearly as could be judged, about the intersection of the sixtieth degree of geographical latitude

* Quarterly Journal of Science. Sept. 1829, p. 3.

with the meridian of 80° west of Greenwich.

But M. Hansteen was led by a more careful consideration of the slight apparent deviations which had been noticed, and of the general disposition on the globe of the lines of dip and variation, to infer the existence of a second point of principal magnetic action in the northern hemisphere. This fact may now, indeed, be regarded as fully established by his recent observations; the isodynamic curves being found to arrange themselves systematically round two poles, the one in Hudson's Bay and the other in Siberia; and to be governed in the courses which they follow, partly by their distances respectively from those points, and partly by a disparity in the absolute attractive force at the points themselves: the maximum intensity in Siberia appearing to be weaker than that in Hudson's Bay, and existing at a point situated in longitude 102° east of Greenwich, which is as nearly as can be judged, 180° from the present position of the corresponding point in Hudson's Bay, and in a latitude somewhat to the north of 60°, but which, it is to be hoped, will soon be more particularly determined.

§ 5. *Progressive Changes of Variation and of Dip.*

(115.) The most singular and unaccountable circumstance relative to terrestrial magnetism remains yet to be noticed; namely, that it does not remain constantly the same in the same place, but undergoes a slow and progressive change. The variation of the compass is itself variable, not merely in different regions of the globe, but at different periods of time. Thus, the needle in London, in the beginning of the seventeenth century, was inclined a few degrees to the eastward of the true north. In 1659 or 1660, it pointed exactly north; or in other words, the variation was reduced to zero; and, of course, London was at that time one of the points of the line of no variation. After this, the variation became westerly, and has continued so to the present time. The line of no variation, therefore, has been progressively, but slowly moving in a westerly direction, and has now passed over to North America.

Similar changes have taken place at Paris; but the line of no variation appears to have passed over that city rather later than it did over London: for it was not till the year 1664 that the magnetic coincided with the true meridian. In 1814, it was 22° 34′ west. In October, 1829, the variation at Paris was ascertained, by M. Arago, to be 22° 12′ 5″ west*.

At London, the westerly variation continued to increase till the year 1818, when it amounted to 24° 30′. This appears to have been its maximum; for since that time it has somewhat diminished, and is at present about 24°.

It appears, from the table given by Mr. Gilpin †, that the annual change in the variation has diminished, in each successive period, since the beginning of the last century. In the preceding century, that is from 1622 to 1692, the annual change was about 10′; from 1723 to 1773, it was about 8′; from 1787 to 1795, about 5′; from that time to 1802, only 1′.2: in 1818 it was reduced to zero.

(116.) The dip has also undergone corresponding changes, though less considerable ones than the variation. In 1680, the dip in London was 73° 30′; in 1723 it was 74° 42′: since which time it has been observed to diminish progressively, though, as it would seem, not quite regularly.

				Authorities and Localities.
In 1773 it was	72°	19′		Dr. Heberden.
1786 „	72	8		Gilpin, Royal
1805 „	70	21		Society's Rooms
				Phil. Trans. for 1806, p. 419.
1818 „	70	34		Capt. Kater, Regent's Park.
1821 „	70	3		Captain Sabine, Chiswick.
1828 „	69	47		Ditto.
1830 „	69	38		Capt. Segelcke, Woolwich.‡

On the continent of Europe the dip has undergone a similar diminution of late years. The dip at the observatory at Paris, in the year 1814, was 68° 36′, according to the determination of M. Bouvard. In June, 1829, it was ascertained by M. Arago to be 67° 41′.3.

(117.) Captain Sabine, by comparing the present dip with that observed for the last fifty years, concludes that the

* Annuaire pour l'An 1830.

† Phil. Trans. for 1806, p. 395.

‡ For the information relative to the last of these determinations, we are indebted to the kindness of Professor Barlow, of Woolwich, who states that Captain Segelcke, of the Norwegian Navy, and a friend of Professor Hansteen, employed in this determination of the dip, the same needle which the latter had with him in his recent tour in Siberia.

mean annual diminution is about 3′. Mr. Barlow finds that these observations accord much more nearly with what would take place on the supposition of a uniform motion of revolution in the magnetic pole round the pole of the earth. From the most authentic observations on the dip and variation of the needle in London, he calculates that the longitude of the northern extremity of the magnetic polar axis which it obeys was, in 1818, 67° 41′ west, and its latitude 75° 2′ north. If we suppose that the motion of this pole has been uniform since the year 1660, when, from the disappearance of variation, its longitude must have been zero, and that it has preserved the same distance from the terrestrial pole, its annual motion of revolution must have been about 25′. 4. It would, therefore, require eight hundred and fifty years to make an entire revolution of 360°. Computing from these data, it would follow that the variation ought to reach its maximum when the longitude of the magnetic pole is 70° 23′ west. It would have arrived at this situation about the year 1823; about which time, as it would appear, the variation was stationary, having attained its real maximum, and having, since that period, actually retroceded.

(118.) On calculating what the dip should be in 1823, according to Mr. Barlow's hypothesis, a very near agreement with actual observation is found to take place. It follows, however, from this hypothesis, that the dip has not an uniform decrease, but that it is changing much more rapidly at this present time than it has ever done since magnetical observations have been made. Its decrease, during the five years preceding 1824, has been nearly half a degree, and it ought to have diminished to an equal extent during the following five years. Mr. Barlow* has computed that in

	The Variation should be	and the Dip
1828 . .	24° 29′ . .	69° 43′
1833 . .	24 26 . .	69 21

The near accordance of these results with what has actually been observed, is considered by him as a strong confirmation of the truth of his hypothesis.

(119.) It would appear, then, both from observation and from theory, that the dip is at present changing more rapidly than the variation; and the theory leads to the expectation that it will continue to decrease together with the dip, for about two hundred and fifty-five years, at the end of which period, that is in 2085, the longitude of the magnetic pole will be 180°; the variation will then be nothing, and the dip only 56°, which will be its minimum; they will then both increase together for the next two hundred and sixty years, when the needle will have its greatest easterly variation, and will then again return towards the north, the variation decreasing, but the dip still increasing, for one hundred and sixty-five years longer, namely, till about the year 2510, when the magnetic pole will be again in the meridian of London; the variation will then be zero, and the dip will amount to 77° 43′. It is to be observed, however, that Mr. Barlow advances this merely as an hypothesis, the truth of which remains to be determined by future experience.

(120.) A curious hypothesis was advanced by Dr. Halley, and supported with some ingenuity, in order to explain the progressive changes that take place in the variation of the compass. He supposes the globe we inhabit to be a mere external shell, enclosing, towards its centre, a detached magnetic nucleus, of a spherical shape, which revolves with the external shell on a similar axis, with nearly the same velocity. He supposes both these spheres to be magnets, having each two poles; but the poles of the one not exactly corresponding in situation with the poles of the other. The difference of the periods of rotation of the two spheres, he conceives to be exceedingly small, yet sufficient to become sensible after the lapse of years, and to occasion a change in the relative situation of the two sets of magnetic poles; and hence would arise changes in the direction of their resulting actions, and corresponding changes in the variation of the magnetic needle. However ingeniously this hypothesis may have been framed, it was too bold and fanciful to have been ever generally adopted. Its author, indeed, has the candour to acknowledge that it is beset with numerous difficulties, which further experience, extended over a long period of time, can alone enable us to remove. He concludes his paper in the Philosophical Transactions in which he has developed his theory, with the following sentence: 'But whether these magnetical poles move altogether with one motion, or

* See his Essay on Magnetic Attractions, 2nd Edition, p. 218.

with several—whether equally or unequally—whether circular or libratory; if circular, about what centre; if libratory, after what manner; are secrets as yet utterly unknown to mankind, and are reserved for the industry of future ages*.'

§ 6. *Diurnal Changes of Variation and Intensity.*

(121.) Independently of the changes already noticed, the position of the magnetic needle is liable to certain slight variations, according to the time of the day, and also according to the season of the year. The daily change in the variation was discovered in 1724 by Mr. George Graham, and has been confirmed by many subsequent observers. This change, however, is exceedingly minute, and requires the most careful observation, and the most delicate instruments to render it sensible, even in the horizontal needle; and it is still more difficult of detection in the dipping needle, which does not admit of the same degree of delicacy of suspension.

(122.) Professor Barlow, to whom the science of magnetism is so much indebted for its more recent improvements, has devised a mode of rendering these diurnal oscillations much more perceptible, by diminishing the ordinary directive power of the needle, through the influence of one or two magnets, placed in such positions with respect to the needle as to counteract, and thereby neutralize, as it were, the terrestrial action. The effect of the ordinary action being thus removed, he was led to expect that the extraordinary cause, whatever it might be, which produced the daily variation, would exhibit its effects much more perceptibly; and thus not only the amount of the changes it produces, but also the period of their taking place, and of the maximum of their operation, might be ascertained with great precision. These expectations have been amply realized by the success of his own experimental researches, and also by those of Mr. Christie, which are detailed in several papers in the 'Philosophical Transactions†.'

(123.) The general result of the experiments of the latter of these observers was, that the deviation of the horizontal needle from the mean position was easterly during the forenoon, and was of greatest amount at about eight o'clock, thence returning quickly to its mean position, which it attained between nine and ten o'clock, after which it became westerly; at first increasing rapidly, so as to reach its maximum at about one o'clock in the afternoon, and then slowly receding during the rest of the day, and arriving at its mean position by about ten o'clock at night. The state of the weather, and more particularly that of the temperature, had considerable influence on the nature and extent of the changes.

(124.) Mr. Christie remarks that the changes which are observed to take place cannot be explained by a change in the directions alone of the terrestrial forces, but that their characters agree, as nearly as we can possibly expect, with the effects that would take place from an increase of intensity at the time that the direction deviates towards the west.

(125.) The occurrence of diurnal changes of intensity at Christiana in Norway have been ascertained by M. Hansteen; the same conclusion being deducible from his observations of the vibrations of a needle very delicately suspended; and also from those of Mr. Christie, made with a different apparatus, and by a totally different method.

(126.) M. Hansteen found that the minimum intensity occurs about half past ten o'clock in the morning, that is, about two hours after the westerly deviation has commenced, and the maximum intensity at half-past seven in the evening, that is, about the same time after the return towards the east. Mr. Christie* found that the terrestrial magnetic intensity is the least between ten and eleven o'clock in the morning; the time, nearly, he observes, when the sun is on the magnetic meridian; that it increases from this time until nine and ten o'clock in the evening; after which it decreases, and continues decreasing, during the morning, until it attains its minimum already stated.

(127.) The general dependence of these variations of magnetic position on diurnal changes of temperature is sufficiently apparent from the results hitherto obtained. But the prosecution of the inquiry involves considerations of another kind, connected with a subject we have not yet touched upon, namely, electro-magnetic and thermo-magnetic phenomena.

(128.) The mean diurnal changes of variation were found by Mr. Canton to

* Phil. Trans. for 1668, p. 220.
† For 1823, 1825, and 1827.

* Philosophical Transactions for 1825, p. 51.

differ at different seasons of the year, being greatest in June and least in December *, and he has given the results of his observations in a tabular form. Mr. Gilpin investigated this subject at a later period, and gives also tables of the diurnal changes of variations in each month, which he found to be very different in different years. The following table contains the results of these different observations *.

Mean Diurnal Changes of Variation.

Months.	Canton in 1759.	Gilpin in 1787.	1793.
January	7′ 8″	10′.2	4′.3
February	8 58	10 .4	4 .6
March	11 17	15 .	8 .5
April	12 26	17 .4	11 .7
May	13 0	18 .9	10 .4
June	13 21	19 .6	12 .6
July	13 14	19 .6	12 .5
August	12 19	19 .4	12 .1
September	11 43	15 .5	9 .8
October	10 36	14 .3	7 .0
November	8 9	11.1	3 .8
December	6 58	8.3	3 .8

Chapter IV.

Theories of Magnetism.

§ 1. *Mechanical Theories.*

(129.) In the general view we have now given of the present state of our knowledge with regard to magnetism, we have strictly confined ourselves to the statement of facts, unmixed with hypothetical speculations as to the nature of the powers from which they proceed. We have solely endeavoured to generalize the facts, as far as their nature and extent would warrant. The result has been their reduction to a small number, such as the mutual attractions and repulsions of magnetic iron according to certain laws,—the induction of these properties on other iron,—the differences in the capacities of receiving and of retaining these properties, existing in different kinds of ferruginous bodies,—and the magnetic influence of the globe of the earth.

(130.) But the human mind is so constituted as to refuse being restrained within the boundaries of a rigid inductive philosophy. Incited by an irresistible desire of exploring the secrets of Nature, it scruples not as to the means of forcing her to disclose them; and borne on the wings of imagination and conjecture, presses forwards with an eagerness which often betrays it into courses widely deviating from the truth. Yet good is often found to result from these erratic excursions of our faculties: they infuse fresh interest into the pursuit of knowledge; they inspire with the hope of success; they invigorate those powers which must be exerted to attain it. The spark which kindles a train of light is sometimes struck out in the conflict of discordant speculation; and amidst a multitude of attempts, some effort, more happy than the rest, elicits an important discovery. No great or comprehensive fact in science was ever established, without being preceded by a bold though sagacious conjecture. Hypothesis of some kind or other is invariably the precursor of truth.

(131.) Magnetism, ever since it occupied the attention of philosophers, has been a fertile soil for hypothesis. That a shapeless and unorganized lump of metal should have the power of drawing towards itself another equally rude and unfashioned piece lying at a distance, or of forcing it to move away, as if both were alive, and animated by some principle of active sympathy; and that all this should take place, whatever may be the number or kind of the intervening bodies, nay even in the apparent absence of any connecting medium, are phenomena of too remarkable a nature not to excite in us a lively curiosity to learn their cause. No wonder that the ancients, who had but imperfect notions of the real objects of philosophy, were impressed with a vague notion of their connexion with immaterial agency. Mag-

* Phil. Trans. for 1759, p. 398.

* Phil. Trans. for 1806, pp. 416, 417.

netic attraction was ascribed by Thales to the secret influence of a species of mind, or soul, residing in magnets. This was also the doctrine taught by Anaxagoras, who extended it to many other phenomena in nature. Others endeavoured to account for the attraction between the loadstone and iron by the vague notion of a kind of sympathy existing between these two bodies. In later times Cornelius Gemma imagined that the connexion between them was established by what he calls invisible rays. Cardan asserted that the iron was attracted because it was of a cold nature, and Costeo de Lodi, because iron was the natural food of the magnet.

(132.) But, consigning these wild vagaries to the oblivion they merit, let us consider whether the phenomena of magnetism are capable of being reduced to any class of physical actions with which we are more familiar. In accounting for a motion which we see take place, we have a natural repugnance to admit of the existence of a power of action at a distance; or, in other words, to conceive that a body can act where itself is not: and we always incline to that supposition which implies the motion to be the effect of impulse. We naturally ask, agreeably to this prepossession, whether the movements of magnetic bodies may not be occasioned by the impulse of some subtile ethereal fluid impinging on their surfaces; emanating, for instance, from one end, and passing into the other, or circulating in invisible currents around the magnets from pole to pole. This fluid might, for instance, be conceived to emanate from one pole, to enter at the other, and permeating the substance of the magnet, again to issue from its former outlet.

Such was the train of thought that obviously occurred to those who first witnessed the arrangement which iron filings, loosely scattered around a magnet, assume in consequence of its influence. The filings have the appearance which would be given by a stream of fluid brushing by them, and turning each individual filament in the direction of its course; which course might accordingly be easily traced in the regular and symmetric curves that are exhibited to the eye. In the infancy of the science, and in the absence of any other hypothesis, many were the speculations advanced as to the mode in which these supposed streams of magnetic fluid produced the observed effects. Descartes was the foremost among those philosophers who laboured to account for all the unexplained movements in nature by the impulsion of fluids circulating in vortices; and he naturally viewed the phenomena of magnetic action as strongly corroborating his system. Euler also, who sought to explain various natural appearances by the intervention of an ethereal fluid, did not fail to apply his favourite hypothesis to the elucidation of magnetism. He even went so far as to imagine the possibility of there existing in the substance of iron numerous canals, through which the ether circulated, furnished with valves which regulated the direction in which it moved. It was not until the phenomena had been examined with greater care, and were rigorously subjected to the inductive process, that juster notions of the nature of the magnetic forces came to be entertained. With the knowledge we now possess of the actual law of magnetic attraction and repulsion, it must be at once perceived that all hypotheses founded on the impulse of a fluid in motion, are irreconcileable with that law, and must therefore be totally discarded.

§ 2. *Theory of Æpinus.*

(133.) The obvious analogy which presents itself between the phenomena of magnetism and those of electricity, naturally suggested the probability that the same mode of explanation might apply to both, and laid the foundation of the first rational theory of magnetism. While Æpinus was intent upon improving the beautiful electrical theory of Franklin, he was struck with the remarkable similarity in the attractions and repulsions exhibited by the tourmaline, when it is heated, to those of magnetic bodies; and it occurred to him that the phenomena of magnetism might be derived from the agency of a peculiar fluid, having properties very similar to those of the electric fluid, but which acted exclusively upon iron. The principal difference between the two sets of phenomena was, that, in the case of electricity, the agent, whatever be its nature, is actually transferred from one body to another; but in magnetism there is merely induction, but never any transference. In as far, however, as respects mere attraction, repulsion, and induction, electricity and magnetism present phenomena that are perfectly pa-

rallel to one another. Franklin's ingenious theory of the two modes of electric agency, the one consisting in an excess, the other in a deficiency of fluid, and the happy explanation it afforded of the opposite electrical states resulting from induced electricity, and its accumulation in the Leyden phial, were applied with great ingenuity by Æpinus to the contrariety of magnetic polarities in the opposite ends of a magnet, and the induction of similar magnetic states in an unmagnetized bar of iron. His system of magnetism, when digested into a series of propositions, may be stated as follows:—

(134.) 1. There exists in all bodies capable of acquiring magnetic properties, a subtile fluid, which may be called the magnetic fluid.

2. The particles of this fluid repel one another with a force which decreases as the distance increases.

3. The particles of the magnetic fluid attract, and are attracted by the particles of iron, with a force varying according to the same law.

4. The particles of iron repel one another according to the same law.

5. The magnetic fluid is incapable of quitting the body in which it is contained, but it is capable of moving within the substance of pure iron and of soft steel without any considerable obstruction. It is more and more impeded in its motion as the steel is tempered harder; and in very hard tempered steel, and in some of the ores of iron, it moves with the greatest difficulty.

(135.) In order to judge of the degree in which the theory is qualified to represent the facts, we must study the several consequences which flow from the above suppositions, and then compare them with the actual phenomena which are presented to our observation.

(136.) Each particle of iron, by the hypothesis, attracts a particle of magnetic fluid, placed at any particular distance, with a certain force. We may conceive that magnetic fluid is gradually added to the particle, until the quantity thus added is such that the force of repulsion which the fluid exerts upon any distant particle of magnetic fluid, exactly balances the attractive force of the iron for that same particle. This quantity may be regarded as the natural quantity of fluid belonging to that particle of iron. According to this definition, therefore, a mass of iron, all the particles of which contain their natural quantity of fluid, must be neutral with regard to its action on any other particle of fluid, and also on any other particle of iron. Such is the condition of unmagnetical iron or steel. Its magnetism is neutral, or in a state of equilibrium.

(137.) But should, from any cause, this state of equilibrium be destroyed, and magnetic fluid be either accumulated beyond its natural quantity as relates to the iron, or reduced below that proportion, the part where this excess or this deficiency exists becomes active —that is, acquires the properties of either a north or a south pole. As the fluid can never pass beyond the surface of the mass of iron in which it is contained, the total quantity residing in that mass must remain precisely the same, whatever be its mode of distribution; and therefore the excess of fluid in those parts where it is accumulated or redundant, must be exactly compensated by the redundant iron, if we may so express it, in those parts where the fluid is deficient. In all cases it will be only the redundant fluid or the redundant iron that constitutes the active parts of the magnet.

(138.) It follows as a direct consequence of the second condition of the hypothesis, that the pole of one magnet in which the fluid is redundant will repel the pole of another magnet in which it is also redundant; because the fluid in each is mutually repulsive of the other.

(139.) From the third condition of the same hypothesis, it likewise follows that the pole having an excess of fluid, or the overcharged pole, as we may call it, of one magnet, will attract and be attracted by the pole in which the fluid is deficient, or the undercharged pole of the other; and this action must be reciprocal.

(140.) It is also a necessary consequence of the fourth condition that the redundant iron in the undercharged pole of one magnet repels every similarly constituted pole in other magnets; because, by the hypothesis, iron repels iron.

(141.) Hence we deduce the general law that similar poles repel, and dissimilar poles attract one another,—a law identical with that we have already deduced from experiment.

(142.) Let us next see what account the theory gives us of the induction of magnetism. If the overcharged pole of a magnet be brought near the end of a bar of iron in its natural or unmagneti

cal state, the redundant fluid in the former, exerting a repulsive influence on the fluid at the nearest end of the latter, will give it a tendency to move towards the remote end. It will obey this tendency, provided the texture of the iron offers no obstruction to its transmission; and a certain portion of the fluid will accordingly be transferred from the near to the remote end. The bar will now exhibit magnetic properties; its near end being undercharged, will possess a polarity of an opposite nature to that of the magnetic pole presented to it; the remote end, being overcharged, will have a polarity of the same kind as the pole of the magnet.

(143.) A series of changes exactly the converse of these will take place when, instead of the overcharged pole, we present the undercharged pole of the magnet to the bar. The redundant iron now attracts the magnetic fluid of the bar, and draws it towards the adjacent end, converting it into an overcharged pole, while the other end, from which the fluid has been drawn, becomes the undercharged pole.

(144.) The effects, however, do not end here. The bar, thus rendered magnetic, reacts upon the magnet from which it had derived its power, and tends to increase the magnetism it originally possessed. This increased magnetism, in its turn, tends to produce an augmentation of the induced magnetism of the bar; and these alternate actions and reactions proceed till all action is balanced and every thing remains quiescent. In soft iron this is accomplished almost in a moment: but in steel the process is somewhat different; for its texture presenting great impediment to the motion of the magnetic fluid, the changes of distribution take place much more slowly, and to a less extent than they do in iron. The adjacent end of a steel bar soon acquires a degree of polarity opposite to that of the end of the magnet presented to it; but the polarity of the same kind travels slowly onwards, and does not reach the other extremity of the bar till after a considerable time; and if the bar be very long, may possibly never reach it.

In this last case, we have a curious phenomenon produced from the influence of a secondary induction; namely, the appearance of a second set of poles, at a certain distance from the first. Thus, if a north pole has been presented, the adjacent end of the bar will be a south pole; at a little distance from this we shall have a north pole; beyond this again will appear another south pole, and perhaps at the furthest end a second north pole. Sometimes, indeed, there will be only three poles, the middle one being of an opposite character to those at the two ends, which are similar to one another.

(145.) Let us now remove the magnet; what will happen to the iron bar? The cause which maintained the magnetic fluid in the forced state of excess at one end, and of deficiency at the other, no longer operating, the fluid will now tend to resume its original state of uniform distribution over the whole mass of iron; and if no obstacle exist in the structure of the iron to impede its motion, it will immediately revert to that state. But if the bar be of steel, which presents obstacles to the passage of the fluid, which the force derived from its tendency to equable diffusion is insufficient to overcome, the fluid which had passed will remain stationary, and the induced magnetism will continue as at first—that is to say, the bar will have been converted into a permanent magnet.

(146.) On the same principle may be explained the effect of hammering, or any other kind of mechanical concussion, in impairing the magnetism of a steel bar; for the tremulous motions excited among the particles will open a passage for the fluid, which will thus escape from the situations where it is condensed, and return to those where it is rarefied.

(147.) Heat, as we have seen, weakens and finally destroys magnetic power; its operation may in like manner be understood, by its occasioning the separation of the particles of iron to a greater distance than before. Hence the interstices will be enlarged, and the obstacles to the motion of the fluid will be diminished, or even entirely removed. The magnetic fluid will thus be enabled to regain its natural state of uniform diffusion among the particles. But independently of its mechanical operation, there are yet many other ways in which heat may be conceived to contribute to the destruction of magnetism. It may change the action of the particles of iron on those of the fluid, or of the fluid on each other, and by altering the distribution of the fluid with respect to the particles of iron, may greatly affect the law of action between one magnet and another.

§ 3. *Correction of Æpinus's Theory.*

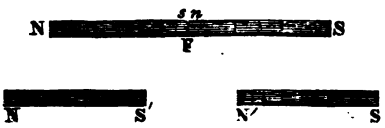
(148.) Thus far do the facts accord with the hypothesis of Æpinus, and thus far may we admit that hypothesis to be a satisfactory explanation of these facts. But in one important application it entirely fails; it does not explain the consequences that are observed to follow on the division of a magnet at the neutral point. Theory would lead us to expect that we should, in this case, obtain the different polarities separate, one in one piece, and the other in the other. The fact we know to be totally different: each part becomes a regular magnet with two poles, one of which retains the character it had before the separation.

Æpinus attempted to remove this difficulty by supposing that, in the act of fracture, a portion of the fluid actually escaped from the overcharged pole, while another portion entered into that which was undercharged,—effects which he conceived might result from the sudden change in the balance of magnetic forces consequent upon the fracture. But this explanation, as Professor Robison remarks, is far from satisfactory.

(149.) The only rational mode of reconciling this fact with the system of Æpinus, is to consider a magnet as an aggregate of small particles of iron, each of which individually has the properties of a separate magnet; that is, has two poles of its own: the arrangement of these particles being such that all the poles are disposed in a regular order of alternation; so that in every part of the mass of iron, each pole of one particle is in contact with the contrary pole of the next in the series. These adjacent poles of course neutralize one another, with regard to their magnetic action, and it is only those which are situated at the extremity of the line, and which are not associated with any other, that constitute the active poles of the entire magnet. Hence it is at the surface, and more particularly at the extremities, that polarity is manifested; and hence when a magnet is broken across, the fractured ends at once exhibit the opposite polarities they had before possessed, but which had been masked by their cohesion.

(150.) A practical illustration of this view of the subject may be afforded by placing a number of small magnets of equal strength in a line, with their opposite poles in contact, as exhibited in *fig.* 41. It will be found that almost the only polarity that is sensible, appears

Fig. 41.



at the two extremities N and S; the intermediate portions formed by the junction of the opposite poles *n* and *s* being, to all appearance, neutral. If the series be broken at any one point as at F, the two portions G and H will immediately present the properties of separate magnets, and the new poles N^1 and S^1 being now separated, exhibit their natural activity.

(151.) According to this view of the subject, the induction of magnetism will consist, not in the actual transference of the magnetic fluid from one extremity to the other of the iron bar which has been rendered magnetic; but in a change of this nature taking place in every particle individually, and by which each particle is converted into a separate magnet.

§ 4. *Theory of two Magnetic Fluids.*

(152.) The theory with respect to magnetism which has of late more generally prevailed, is founded on the supposition, that its phenomena are occasioned by the agency of two magnetic fluids, residing in the particles of iron, and incapable of quitting them; one of which fluids imparts the northern and the other the southern polarity. They have been denominated respectively the *Austral* and *Boreal* fluids. The particles of each of these two kinds of fluids attract those of the other, but repel those of the same kind. When in combination with each other, these fluids are neutral and inert; each becoming active only when separate. The decomposition of the united fluids is effected by the inductive influence of either the one or the other when acting independently. It is obvious that, as far as regards the distribution and action of the two magnetic fluids in each individual particle, this theory is precisely similar to that of the two electric fluids, of which an account has been already given in our Treatise on Electricity; it is therefore unnecessary to pursue its development in those particulars, for the reader need only refer to

that treatise, and substituting the terms austral and boreal fluids for those of vitreous and resinous electricities, will find that all the details of the electrical theory will apply to that of magnetism.

(153.) But however the laws of the theory of a double magnetic fluid may be analogous or identical with those of the theory of a double electrical fluid, their application is somewhat different in the two cases, in consequence of the difference of circumstances under which they act. The electrical fluids, when decomposed or separated from each other, are capable of being extensively transferred along the particles of bodies, and of being collected and accumulated at the surfaces, where they have a tendency to escape; and where, if that tendency exceed a certain limit, they actually do escape, either passing into the bodies in immediate contact, or flying off through the air to distant bodies. In this manner each kind of fluid may be separately, and in any quantity, transferred from one body to another. Nothing of this kind takes place with regard to magnetism; the magnetic fluids are never found to quit the bodies to which they are attached, however small those bodies, however intimate the contact with other iron, however long the contact may be continued, and however powerful the forces by which the fluids are impelled. The phenomena consequent on the division or fracture of a magnet lead us also to the conclusion that no sensible quantity of either austral or boreal fluid is ever transported from one part to another of the same piece of iron or steel. Hence, in order to accommodate the theory to these facts, we must introduce as a new condition of the hypothesis on which it is founded, that within the substance of a magnetized body, the two magnetic fluids, when they are decomposed by the influence of magnetizing forces, undergo displacements to an insensible distance only.

(154.) It is not necessary to determine whether the extremely small spaces, within which these displacements and motions of the magnetic fluids are restricted, be actually the same as the spaces occupied by the constituent molecules of the iron; it is sufficient for the purposes both of theory and of the calculations founded upon that theory, that they be extremely small in comparison with the whole volume of the body, or even with the smallest dimensions that ever come under the cognizance of our senses. Poisson, who has given us a beautiful developement of this theory*, designates these very minute spaces or portions of a magnetic body by the name of the *magnetic elements* of that body. There is also no necessity for making any particular supposition with regard to the form or respective disposition of these elements, provided we simply consider them as insulated from each other by intervals impermeable to either of the magnetic fluids.

(155.) The quantities of each kind of fluid contained in every magnetic element must be considered, with reference to all our experiments, and to all the powers we can apply, as without limit; that is to say, the forces we can command, in any magnetizing process, are never sufficient to exhaust or separate the whole of the fluids. For, when a body is magnetized by the inductive influence of a neighbouring magnet, the intensity of its magnetic state, as shown by its effects, increases without limit, in proportion as we employ a magnet of greater force; which, of course, implies that we have not yet effected the decomposition or separation of the whole quantity of the neutral or combined fluid which that body contains. In like manner, we find it impossible to separate completely the two electric fluids contained in any particular body.

(156.) Besides the obstacles, which appear to be insuperable, to the transmission of the magnetic fluids from one magnetic element to another, there must exist, in the substance of certain bodies, some impediment of another kind, which obstructs the motion of the fluids from one part to another of the same magnetic element. The effect of this power, which is somewhat analogous to the force of friction, is to arrest the particles of both fluids in the situations which they occupy; and thus to oppose, in the first place, the separation of these fluids, and, in the next, their return to the situations from which they had been displaced, and where they would unite to recompose a neutral fluid. This force is termed, by Poisson, the *coercive force*. In soft iron the coercive force is either wanting, or is extremely feeble; in steel and in the loadstone it is very energetic; and it exists in various degrees of intensity in

* Mémoires de l'Institut de France, tome v., p. 247. The introduction to this memoir is given in the Annales de Chimie, tome xxv., p. 113.

different kinds of steel. This coercive force, which exists in iron with regard to the magnetic fluids, is analogous in all respects to the resistance which glass, resin, and other non-conducting bodies, present to the passage of the electric fluids through their substance. Having thus established the foundations of the hypothesis of a double magnetic fluid adopted to the particular circumstances of the case, we must next endeavour to ascertain precisely the distribution of the austral and boreal fluids in magnetized bodies, conformably with these principles; and afterwards examine the nature of their combined actions upon bodies at a distance.

(157.) For this purpose, we may first take the simpler case of a cylindrical needle of soft iron, of very small diameter, and of any given length, as representing an elementary longitudinal filament of that metal. In the natural state of the needle, the two fluids it contains are united in equal proportions throughout its substance, so that their actions, being equal and opposite at all distances, totally destroy each other, and no sign of magnetism is exhibited. If we next suppose these fluids to be subjected to the action of magnetizing forces, proceeding from one or more centres, situated in the line of the axis of the needle produced, these forces will now cause the fluids to separate from each other; but each particle of austral or boreal fluid can, by the hypothesis, move only a very short distance from its primitive situation; and the two fluids, in their new arrangement, will succeed each other alternately, throughout the length of the needle, which will, accordingly, be divided into very small portions, composing a series, each part of which will contain, as it did in the neutral state, the two fluids in equal quantities. The united actions of every particle of decomposed fluid in this series upon a particle of magnetic fluid in any particular situation, compose a resultant force, the intensity and direction of which remain to be determined by the application of mathematical analysis.

(158.) We may now proceed to consider the more complicated case of a magnetized body of indeterminate form and dimensions. Attention must here be paid to the lines or directions in which the separation of the two fluids takes place throughout its substance, and in which they are arranged alternately, as we have just seen exemplified in the case of the simple filament. These lines or filaments will, in general, be curved; the nature of the curvatures depending on the form of the body, and on the external forces which act on the two fluids. They are termed by Poisson *lines of magnetization*, and may be considered as constituted by series of magnetic elements, following one another in the same regular consecutive order of polar arrangement. We have to determine, then, for each point of the body which is the subject of investigation, the direction of the line of magnetization, which is also the line of polarity; and the action of the magnetic element on any other point given in position, either within or without the body. This action is the difference of the forces exerted by the two fluids contained in the element, arising from the slight separation of the austral and boreal particles, which constitutes the state of polarity. It may excite surprise that forces depending on such small differential distances as those of the two centres of austral and boreal forces in each magnetical element, should, nevertheless, be capable of producing mechanical effects so considerable as those exhibited by the magnetic attractions and repulsions of bodies. By applying to the subject the methods of analytical investigation, Poisson arrived at the conclusion, that the result of the action of all the magnetical elements of a magnetized body is a force equivalent to the action of a very thin stratum, covering the whole surface of the body, and formed of the two fluids, the austral and the boreal, occupying different parts of it. We have a similar instance in the case of electrical attractions and repulsions of mechanical effects, sometimes very powerful, being produced by strata of fluids collected at the surfaces of conductors, and having a thickness so exceedingly minute as to be inappreciable by any of our senses. As these observed effects of the two magnetic agents result only from the differences of two contrary powers, we can form no estimate of the real magnitude of the forces belonging to each separate power, that is, to each of the two portions of austral or boreal fluid belonging to the same magnetic element; but can only infer that they are incomparably greater than the resulting forces which are actually in operation, and of which we witness the effects.

(159.) In the memoir on the Theory

of Magnetism, already referred to, M. Poisson deduces, from the theory above stated, the analytical equations which express, for all possible cases, the laws of the distribution of magnetism within bodies that are rendered magnetical by induction, and those of the actions, whether attractive or repulsive, which they exert on points given in position. The first problem to be resolved is to reduce the resultants of all the attractions and repulsions of the magnetic elements of a magnetized body, of any imaginable form, on such points, situated either within or without the surface, to three directions at right angles to one another. By adding to the resultants which relate to any interior point those of the external magnetic forces which act upon the body, he obtains the whole forces which tend to separate the two fluids that are united at that particular point. Were the matter of the body to oppose no sensible degree of resistance to the displacement of the fluids in each magnetic element, or, in other words, if there were no coercive force, it would be necessary, in order that there might be an equilibrium, that the attractions and repulsions should destroy one another; or, speaking algebraically, that their sum should be equal to zero; since, if any of them were uncompensated, they would effect a new decomposition of the neutral fluid, which may be regarded as inexhaustible, and the magnetic state of the body would be altered. The sum of the resultants must, therefore, be made equal to zero, with respect to each of the three rectangular directions to which they are referred. The equations of equilibrium, thus formed, will always be possible, and they will serve to determine, for each point of a magnetized body, the three unknown quantities which they comprehend; namely, the intensity of the action of a magnetic element on a given point, and the two angles which determine the corresponding direction of the line of polarity. At the extremities of each element, these joint resultants will not vanish; they will give rise to pressures from within each element, tending outwards, and counterbalanced by the obstacle, of which the nature is unknown, but which opposes the passage of the fluid from one element to another, and also its escape from the surface.

(160.) When the coercive force of the magnetized body is also taken into account, it will then be sufficient for the magnetic equilibrium that the resultant of all the exterior and interior forces, acting upon any point of the body, nowhere exceeds the given magnitude of the coercive force: so that, in this case, the equilibrium may take place in an infinitude of different ways, and the problem is, in this respect, wholly indeterminate. This indeterminateness is a source of considerable difficulty in the resolution of questions of this nature. The following general consequence, however, may be deduced from the equations of magnetic equilibrium formed in the manner above described; namely, that although in a solid body, magnetized by induction, the austral and boreal fluids are distributed in an active state throughout the whole mass of that body, yet the attractions and repulsions which it exerts externally are precisely the same as if they proceeded from a very thin stratum of each fluid, occupying the surface only, both fluids being in equal quantities, and distributed in such a manner as that their total action upon all the points in the interior of the body is equal to nothing. If the body be hollow, or contain an empty space within it, and if the centres from which magnetic forces proceed be situated within this space, the body must be considered as terminated by two thin strata of fluid, situated, the one on the external, and the other on the internal surface; and the action of these two strata on any point within the substance of the body, joined to that of all the given centres of magnetic action, must produce a perfect equilibrium; and, in this case, the two fluids may be in different quantities in each of the thin strata, provided that they be always in equal quantities in the two surfaces taken together.

(161.) Thus it appears, that the theory of magnetic attractions and repulsions is reduced to the same principles, and leads to the same formulæ, as the theory of electric forces in conducting bodies; and the perfect correspondence between the two may be illustrated in the following manner. We may suppose an aggregate mass composed of minute grains of metal, or other conductor of electricity, each grain being of so small a size that its dimensions may be neglected in comparison with the whole mass, and each being surrounded by a substance impermeable to electri-

city, but not sensibly adding to its bulk. On bringing a body thus constituted near an electrified body, every one of the grains would immediately become electrical by induction; and, in this condition of the body, it has been mathematically proved that the attractions and repulsions which the body would exert externally, would be the same with those of a homogeneous conducting body of the same form and size, subjected to the same external forces: although, in the latter case, the two electric fluids would be transferred to the opposite extremities of the body, while, in the former, they would be obliged to remain in the constituent masses to which they originally belonged. An electrical body, constituted in the manner here supposed, presents us with a disposition exactly analogous to that of a magnetical body; and is therefore calculated to give us a very distinct idea of the distribution of the magnetic fluids when that body is magnetized. The electricity inherent in the ourmaline appears to be disposed in the manner above described; and this stone accordingly affords an excellent illustration of the hypothesis under our consideration. See *Electricity*, § 197.

(162.) Another general consequence of the theory is, that a magnetic needle, placed in the interior of a hollow sphere of soft iron, and so small as not to exert any sensible influence on the sphere, will not be subject to any magnetic action from a magnetic force proceeding from a point external to the sphere; or, in other words, all magnetic action, whether of the earth or of any number of magnets placed without the hollow sphere, will be completely intercepted by the sphere with reference to all magnetic bodies contained in its interior. And conversely, such hollow sphere will totally prevent the action of a magnet placed within it from being exerted on any body placed without the sphere.

(163.) The formulæ derived from this theory have been applied by Poisson to another case, which, as we shall afterwards find, is one of considerable practical importance in navigation, namely, that of a hollow sphere of iron, magnetized by the influence of the earth, that is, by the action of a force of which the origin is very remote, and which may, therefore, be considered as uniform in magnitude, and acting in parallel directions on all the points of the body in question. From the resolution of the equations of magnetic equilibrium obtained in this case, it appears that although the magnetism is by no means confined to the superficial strata of the sphere, and although its intensity may be determined for any particular point of the solid mass of the shell, yet the magnitude of the three component forces produced by it is wholly independent of the thickness of the shell, and is determined only by the radius of the external surface, and by the co-ordinates belonging to the position of the point on which the forces act. When the distance of this point from the centre of the sphere is very great, compared with the radius, each of the three forces is very nearly as the cube of the radius directly, and as the cube of the distance inversely. We shall have occasion, in a future chapter, to notice the remarkable coincidence of the results of observation with the deductions from this theory, affording a very important confirmation of the accuracy both of the analysis itself, and of the theory from which it is derived.

(164.) In a subsequent memoir*, M. Poisson extends his researches so as to obtain a more diversified comparison of the theory with the phenomena; and with this view resolves the general equations he had before established, in the case of bodies having forms less simple than that of the sphere. Such a resolution, however, is attainable only in a very limited number of cases, of which the elliptic spheroid is an example. After giving the formulæ relating to a spheroid of which the axes have any imaginable relations to each other, he particularly considers the two opposite cases of spheroids extremely flattened and extremely elongated. The former may represent a plate, of which the thickness varies very slowly near the centre, and decreases from the point to the circumference; for its action on points near its centre must be sensibly the same as that of any other plate of uniform thickness and of very great extent. The latter, or the extremely elongated spheroid, approaches very nearly to the form of a needle or bar, of which the diameter decreases from the middle to the extremities, varying at first very slowly; and its action on points near its middle can differ but little from that of a bar of which the diameter is constant, and very small in proportion to its length. The consideration of these three cases, which readily admit of the application of the analytical formulæ, is of considerable

* Mémoires de l'Institut, tome v., p. 481.

importance, as they allow of a strict comparison of the results of experiment with the deductions from theory; and the accurate accordance which has been obtained between them, in every instance in which such a comparison has been instituted, affords the strongest evidence of the correctness of the views on which that theory is founded.

(165.) It has already been observed that we have no data for determining the question as to the size of the magnetic elements, compared with that of the constituent molecules: we know not whether they are coincident with these molecules, or whether they occupy only the interstices between the molecules: neither can we determine whether they do not actually comprehend certain definite aggregates of molecules, or whether they are constituted in the intervals of these aggregates. All that we can be certain of is, that the sum of all the magnetic elements, added to the sum of all the unmagnetic elements (that is, the spaces, whether occupied by matter or not, which are devoid of magnetic fluid), must together make up the total apparent volume of the body under consideration. Now the ratio between these two sums may vary, not only in different kinds of bodies, but also in the same body, in different circumstances. It may, for instance, be very materially affected by changes of temperature; and this consideration will probably furnish a key to the explanation of many of the anomalous appearances we have already had occasion to notice in § 49.

(166.) The hypothesis of two magnetic fluids was first propounded by Wilke and Brugmann; but the first real foundations of the theory were laid by Coulomb, who, by the exercise of singular perseverance and sagacity, prepared and established all the physical principles upon which it rests. It has recently occupied the attention of Poisson, and appears to have received its last finish from his masterly hand; for by applying to it the refinements of modern analysis, this distinguished mathematician has succeeded in discovering formulæ which represent, numerically, all the principal phenomena of the science, even in their minutest details, and which furnish us with a ready and consistent explanation of the physical mode by which they are produced.*

(167.) Professor Prevost, of Geneva*, has laboured to frame a theory of magnetism which shall dispense with all attractive or repulsive agencies, and in which all the phenomena shall be resolvable into the effects of impulsion. For this purpose he admits two magnetic fluids, each giving its respective polarity to the two ends of a magnet, and neutralizing each other by combination; but adopting the hypothesis of Le Sage, as to the existence of another infinitely more subtile fluid, pervading all space, and giving rise by its inconceivably rapid movements to all the phenomena of gravitation, cohesion, and chemical attraction, he supposes the magnetic fluids themselves to be set in motion by this primary and universal agent. But it would be impossible in this place to engage in the development of so abstruse and complicated a system as this.

Chapter V.

Methods of making Artificial Magnets.

§ 1. *General Principles.*

(168.) The art of communicating magnetic power to bodies capable of retaining it, is founded on the proper application of the principles already explained; and the practical results of experience in this art have, as might be expected, furnished some of the most interesting illustrations of the theory of magnetism. We have seen that acquired magnetism of every kind, whether temporary or permanent, of which the origin can be traced, has been derived, by induction, from a similar power already existing in some other body. In this respect, then, it differs from electricity, which may be elicited from bodies all of which were previously in a neutral state, by a variety of processes either of a mechanical or chemical nature. But the body which is the cause of magnetism in another body must itself be in an active state of magnetism, and may be either a magnet, whether natural or artificial, or else it must be the globe of the earth itself: it is therefore highly probable, that the magnetism of the earth is the original source of all other magnetism. This view of the subject excludes, of course, all consideration of electro-magnetic influence, which belongs to another division of the science, hereafter to be treated of. It will then be shewn that electricity in

* A popular view of this theory is given by Biot, in a note to his French translation of Fischer's Physique Méchanique, 4th edition, page 342.

* Sur l'Origine des Forces Magnétiques. 8vo. Genève, 1788.

motion is a source of magnetism, and that strong grounds exist for the belief, that even the magnetism of the earth has its origin in electric currents circulating round the equatorial regions.

In giving an account of the methods of procuring artificial magnets, we shall begin with those which depend solely on this source of magnetic power, and which would enable us to obtain them if we were unprovided with any instrument previously magnetized.

(169.) The success of every plan that can be put in practice for obtaining magnets must depend on two circumstances: first, the efficacy of the induction; and, secondly, the fixation of the magnetism that has been induced. That quality and temperament of steel which is most favourable to the former, is least favourable to the latter of these objects; but various methods may be devised which shall answer both these intentions. The particular purposes intended to be answered by the magnetic instrument we are constructing, will frequently determine our preference of one or other of these methods, as well as guide us in the choice of the material to be used, and of the form and dimensions to be given to it.

(170.) Magnetism is most readily communicated to an unmagnetic bar of iron or steel by means of certain combinations of steel bars already magnetized to saturation, which combinations may be regarded as highly-charged magnetic batteries ready for action, and capable of exerting a powerful influence, in inducing magnetism, on all the iron in their vicinity. But an apparatus of this kind cannot at all times be commanded, nor can it at once be constructed: it must be the result of a long preliminary process, of which the object is to impart to each single bar additional quantities of magnetism, until it has acquired, by gradual steps, the full measure it is capable of retaining. We shall first, then, point out the methods of magnetizing those bars which are to compose the apparatus or battery just mentioned.

§ 2. *Method by Percussion.*

(171.) The most advantageous form for the steel bars that are to be employed for this purpose, is that of a rectangular prism, of which the length is about ten times the breadth, and about twenty times the thickness. Six or eight bars of this kind, and of equal size in every respect, should be provided. We have already seen that a certain degree of magnetism may be given to each of these bars by a few blows with a hammer, while they are held in a vertical position (§ 6). This effect results, as we have also seen (§ 107), from the direct inductive power of the earth. But the efficacy of this power will be very considerably increased, if it be combined with the inductive influence of other masses of iron placed near it, or in contact with it: notwithstanding the iron itself, which thus adds to the effect, derives its own power from the same source, namely, the magnetism of the earth. Thus, Mr. Scoresby found that a steel bar which acquired a feeble magnetism by being hammered vertically when resting upon stone or pewter, received a considerable accession of power when subjected to the same degree of hammering while it was placed upon a parlour poker, also kept in a vertical position. The poker, under these circumstances, became strongly magnetic, and in this state exerted upon the bar a much more powerful inductive influence than the earth alone could have done. Hence the magnetism of an iron bar, although temporary and dependent on position alone, may serve as a very important auxiliary in the development of the magnetism in steel bars, which is capable of being permanently retained. This is, in fact, the great principle on which the art of making artificial magnets of high power is founded.

(172.) The effect of the auxiliary iron bar, or of the poker used in the above experiment, is greater in proportion as it is longer; but as it would not be convenient to employ a bar of iron beyond a certain length, the magnetizing process may be continued by the aid of a still more powerful auxiliary, namely, very long bars of soft steel. Mr. Scoresby provided himself with two bars of this description, thirty inches long, and one inch broad; and also with a large bar of soft iron. This iron bar was first hammered in a vertical position. It was then laid on the ground, with its acquired south pole towards the south, and upon that end of it the large steel bars were made to rest while they were hammered; they were also hammered upon each other. On the summit of one of the large steel bars, each of the small bars (which were eight inches long, and half an inch broad), held also vertically, was hammered in succession. In a few minutes they had all received considerable

magnetic power. He then had recourse to other methods, of which we are presently to speak, for still further increasing their power, till they were saturated with magnetism.

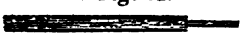
(173.) It may here be remarked, that in this, as well as in every other method for procuring artificial magnets, we advance only by successive steps, gaining a little additional power by each successful process, and employing that which has been acquired by one bar in contributing to the increase of the power of another; while this in its turn gives us the means of reacting upon the first. This we are enabled to do in consequence of the remarkable circumstance attending the induction of magnetism, and to which we have already adverted (§ 23), namely, that the power of the magnet which excites magnetism in another body, is itself increased, instead of being diminished, by such excitation. Hence, by proper management, the power of the several parts of the apparatus is capable of continual increase, limited only by their capacity for receiving and retaining magnetism.

(174.) After having in this way magnetized, by the help of terrestrial magnetism, a certain number of steel bars, we may proceed with them in imparting magnetism to others; and being thus provided with a stronger power, may, in our subsequent operations, dispense with that which we had at first employed.

§ 3. *Method by simple Juxtaposition.*

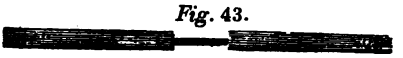
(175.) Simple induction by juxtaposition with one or more powerful magnets may suffice for the impregnation of very small magnets. But, for this purpose, it is not sufficient to place the latter in contact with one of the poles of a magnet, in the manner represented in the following figure (*fig.* 42); be-

Fig. 42.



cause, although the small bar or needle becomes magnetic by remaining a sufficient time subjected to the influence of the large magnet, yet we find that its two ends do not exhibit a magnetism of equal strength. That which has been in contact with the magnet appears to be the most powerful, in consequence of its magnetism being more concentrated at the very extremity; while in the remoter end it is more diffused and therefore less energetic. This inequality is in a great measure remedied by employing two magnets of as nearly equal power as possible, with their dissimilar poles fronting each other, and placing the needle to be magnetized in a line between them; as shown in *fig.* 43.

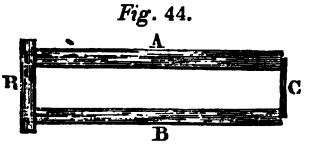
Fig. 43.



The effect of such a combination is always more than twice as great as that of each of the magnets when employed singly. It is difficult, however, even with every precaution, always to avoid the superinduction of consecutive poles in the intermediate parts of the needle.

(176.) The principle we have already referred to, of the increase of power which a magnet acquires by inducing magnetism on other bodies, may here again be applied in augmenting the influence of the magnets we employ in the preceding case. If a long bar of soft iron be applied to each of the poles of these magnets which are most distant from the needle to be subjected to their action, the power of the magnets will be greatly augmented. A more convenient, and perhaps equally efficacious method, is to place the magnets A and B, parallel to each other (*fig.* 44), while the small

Fig. 44.



bar C, to be magnetized, is in contact with the two dissimilar poles at one end; and to unite those at the other end by a bar of soft iron, R. This bar becomes strongly magnetical by the joint induction of both the magnets, and the magnetism it thus acquires reacts powerfully in strengthening the magnets themselves; and the needle which connects their other poles participates in this augmentation of effect. These auxiliary pieces of soft iron, which serve to retain and concentrate the magnetism of steel bars, are called *armatures*.

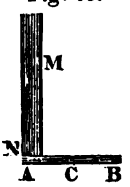
(177.) Were the theory of Æpinus, in its original form, perfectly correct, nothing more would be required for impregnating steel bars with all the magnetism they are capable of receiving than following the methods we have now

pointed out. But we have seen reason to conclude that this theory can be applicable only to the minutest individual particles of which magnetic bodies are composed, and that a magnet should really be viewed as an aggregate of an indefinite number of minute magnets. This consideration cannot but have an important influence on the art of imparting magnetism to such an aggregate; as it will lead us to apply our means to effect, as far as it is in our power, a change in the magnetic state of each portion of the aggregate. The greater the proximity of the pole of the magnet which is to effect this change, to the part in which the change is to be produced, the greater will be the effect produced. Agreeably to this view of the subject, we shall succeed in converting a steel bar into a magnet of greatest power, by subjecting every part of the surface of the bar successively to the contact of the magnetizing pole. Let us trace the consequences of the practical application of this principle.

§ 4. *Method by the Single Touch.*

(178.) One of the earliest methods which was employed for giving magnetism to a bar C (*fig.* 45), was to lay it flat

Fig. 45.



on a table, and placing an artificial magnet, M, on one of its ends, A, and at right angles to it, to slide it along the surface of the bar till it arrived at the other end B; and then, lifting it cautiously to a sufficient height to render its inductive influence insensible, to bring it down again to its former situation, and renew the operation. This was repeated several times on each of the surfaces of the bar, the pole of the magnet being always passed in the same direction, and the same pole employed.

It is evident that when the magnet is first applied to the end of the bar, it will induce in that end a polarity of the opposite kind to that of the pole N of the magnet which is in contact with it. Let us suppose, for the convenience of explanation, that this is a north pole; the end A of the bar to which it is first applied will first become a south pole, and the portions at a little distance from that end will acquire an equal degree of northern polarity. But as the magnet advances along the bar, a similar change will be induced in each successive particle of the surface which it approaches and touches; that is, each particle will now be converted into a south pole, although it had before been rendered a north pole. In as far as this takes place, therefore, the advance of the magnet reverses the effect it had at first produced. In like manner, the magnet has no sooner quitted the end to which it was first applied, than it tends to induce in it the northern polarity, at the same time that it renders the part which it then touches, a south pole. The same succession of changes, and reversal of the magnetism of each part, takes place during the whole of the progress of the magnet along the bar, with the exception of the end which it touches last. It leaves this end of the bar in the state of a south pole, while the other end remains a north pole. The intermediate parts may be considered as constituting a series of small magnets, with all their north poles turned towards A, and their south poles towards B.

(179.) However conformable to theory this method of magnetizing may appear to be, experience shows that it is very little superior to that by simple contact. It has also, like that method, the disadvantage of frequently producing consecutive poles; and these more especially occur when the bar to be magnetized is of some length, or consists of very hard steel. They are also very readily produced if care be not taken to prevent the magnet from resting for a longer time on some portions of the bar than on the rest; for in this case the poles are multiplied very much in the manner stated in a former chapter (§ 30, 31); a pole of one kind being formed at the point where the contact has been too long protracted, and two others of the contrary denomination in the immediate vicinity.

(180.) A singular circumstance characterizes this method of magnetizing by *touching*, as it is called. If, after a bar has been impregnated with as much magnetism as it is capable of receiving by this method from a strong magnet, an attempt be made to increase the effect by renewing the same operation upon the bar with a weaker magnet than the one that was first employed, the

immediate result is a loss instead of an augmentation of power; and the bar remains only magnetized to a degree corresponding with the lesser power of the last magnet by which it has been touched. The reason of this will easily be understood, when we consider that the first effect produced by the second magnet is, to reverse the poles which already exist in the bar, and afterwards to induce the same kind of polarity; but this last effect it can produce only in a degree corresponding to its own strength. It therefore destroys, during the former part of the operation, more than it can supply in the latter.

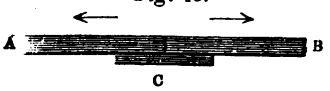
The only exception which might be conceived to exist to this destructive action of a weaker magnet, would be in the case where the latter was composed of a very soft material, so that the magnetism of the bar was capable of affecting its polarity, so as to destroy it when of a similar kind to the part of the bar with which it came in contact, and convert it into an opposite polarity.

(181.) An attentive consideration of the stages of the process we have detailed, will show us that the destructive operation of the second magnet is produced chiefly in the first half of the bar; for if the weaker magnet were first applied to the middle of the bar, and then made to slide on to the end in the same direction as before, over the latter half, its effect on the first half would only tend to strengthen the polarity already impressed upon it. Nor would there, in that case, be any injurious effect produced if the second magnet were sufficiently soft in its texture to admit of having its polarity changed by the magnetism of the bar. This consideration leads us to another important stage in the progress of improvement in the art we are studying.

§ 5. *Dr. Knight's Method.*

(182.) This improvement consists in employing two magnets in the same operation, applying two dissimilar poles of these magnets each to a different half of the bar to be impregnated, and confining its action to that portion of the bar, which of course should be much smaller than the magnets. For this purpose the two magnets are to be joined lengthwise, with their dissimilar poles in contact, and laid on the bar to be magnetized, in the manner represented in *fig.* 46, where A and B are the magnets, and C the bar to be magnetized; so that the

Fig. 46.



point of junction of the magnets shall be immediately over the middle of the bar. Then separating the magnets, by drawing them opposite ways in the direction of their length as far as the extremities of the small bar, they are next to be removed to a considerable distance, and again joined; and afterwards laid a second time on the middle of the bar, in the same manner as at first. This operation is to be repeated several times on each of the sides of the bar. By this method, which was first practised by Dr. Gowan Knight about the middle of the last century, steel bars could be rendered much more powerfully magnetic than by any of the means before in use.

(183.) The great superiority of Dr. Knight's method is owing, not merely to the circumstance before noticed—that each pole of the magnets acts only upon that half of the bar which is intended to receive a magnetism of an opposite kind, and that its inductive effect on the other half has never to be destroyed,—but also to the inductive influence of the two poles being combined together during the whole of the operation. In every portion of the bar which lies between the two poles of the magnets that are thus applied, their influence conspires to induce the kind of magnetism that it is desired to produce. In those portions of the bar, indeed, which lie on the other sides of the poles of the magnets, they oppose each other: but it will be perceived that their effect is here only that resulting from the difference of their respective influences; while, in the former case, when they act upon the intermediate portions, it is as the sum of that influence. The superiority of the combined influence is even greater than the united powers of the single magnets, as we have already had occasion to point out.

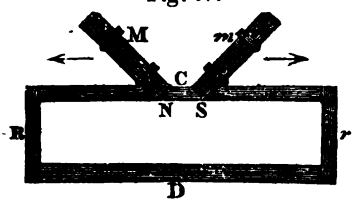
§ 6. *Duhamel's Method.*

(184.) If the magnets employed be large and powerful, and the bars very short and slender, it is easy, by the preceding method, to magnetize them to saturation. Soon after the publication of Dr. Knight's method, small bars thus magnetized were distributed over Europe, and were eagerly sought after by the cultivators of natural philosophy. It was

soon found, however, that the attempt to magnetize bars of a greater length by this process was generally less successful, or at least failed in giving to them all the power of which they were susceptible. Philosophers therefore renewed their efforts to devise methods of greater and more universal efficiency. M. Duhamel, of the French Academy of Sciences, in conjunction with M. Authcaume, at length devised the following plan, which was found to succeed even with bars of considerable dimensions.

(185.) He first laid the two bars of steel intended to be magnetized, and which were made of equal length, parallel to each other, C D (see *fig.* 47), and

Fig. 47.



connected their extremities by two shorter bars of soft iron, R *r*, so as to form altogether a right-angled parallelogram. Then taking two parcels of bars already magnetized, M *m*, the separate bars of each parcel being placed with their respective poles in the same directions, and firmly tied together, he brought the poles of opposite kinds, N, S, into contact over the middle of one of the steel bars forming the parallelogram, giving them a certain inclination to the bars as seen in the figure. The angle they formed with each bar was generally about forty-five degrees, so that they formed with each other a right angle. Then separating them from each other, he made them slide gently, and with an equable motion, towards the extremities of the bar. This operation was repeated on the same bar as often as appeared requisite. The inclined parcels of magnets were then taken to the opposite bar of the parallelogram, and applied to them in the same manner; taking care, however, to reverse the disposition of the poles of the magnets, so that the side on which the north pole was placed in the one case, was occupied by the south pole in the other. After the bars had been rubbed sufficiently on the one side, they were turned on the other side, and the same operations repeated on them in that situation.

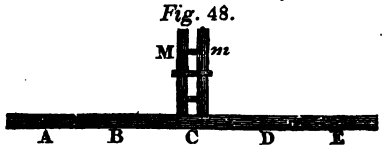
(186.) It is evident, that in as far as the magnets exert their conjoined influence on the portions of the bars that lie between them, and act only upon their respective halves of the bars, the method of Duhamel possesses all the advantages of that of Dr. Knight. The combination of many separate magnets in each bundle, however, gives them greater power in operating the requisite inductions—a power, indeed, which appears to be considerably greater than that which a single magnet of the same size as that of the combined magnets would possess. But the principal improvement in Duhamel's plan consists in the disposition of the bars in a parallelogram in conjunction with connecting pieces of soft iron, which, acting as armatures, afford an advantage of a similar kind to that already explained in § 176. In proportion as the steel bars acquire magnetism, these connecting pieces participate in the acquisition of a similar power, and serve to retain it in the bars themselves; just as the electricity which is imparted to the inner coating of a Leyden jar is retained by the reciprocal influence of the induced and contrary electricity of the outer coating. The magnetism of the bars is retained by a similar influence, and greater facility is thus afforded to increase its amount by the subsequent additions it is receiving from the action of the magnets as they pass along the surface.

§ 7. *Method by Double Touch: Process of Mitchell.*

(187.) While Duhamel was endeavouring to perfect his method in France, the same object was occupying the attention of experimental philosophers in England; and much about the same period new processes for magnetizing bars were invented by Mitchell and by Canton.

(188.) Mr. Mitchell, of Cambridge, published his improved method in 1750. He employed two parcels of strongly magnetized bars (M *m*, *fig.* 48), joined

Fig. 48.



in a manner similar to those above described, and placed them parallel to each other, but with the poles of each parcel reversed, leaving between the two parcels an interval of about a quarter or a

third of an inch. He then arranged a number of equal steel bars (A, B, C, D, E) in a straight line, and made one extremity of the conjoined magnets slide at right angles over the line of steel bars. He did not, however, limit himself to one direction, but moved them backwards and forwards the whole length of the united surfaces of the bars; repeating the operation on each side until he had obtained as great an effect as possible.

In order to equalize as much as possible the magnetic power of the two ends of each bar, it is expedient to commence each operation by laying the conjoined magnets on the middle of the line of bars, and to pass the magnets over each half of the line an equal number of times; at the conclusion of which, the magnets being brought again to the middle, they should be raised perpendicularly, so as not to disturb the lateral effects which had been produced. Mr. Mitchell found that the steel bars B, C, D, which were intermediate in the series, acquired by this process a very great degree of magnetic power. Those which formed the extreme bars of the series A, D, were much less impregnated; but by removing them from this situation, and transferring them to the middle of the series, and then repeating the same operations, they quickly acquired the same degree of magnetism as the rest.

(189.) The process above described, which soon acquired much celebrity, was called *the method by double touch*; and it is asserted by its inventor, that two magnets will impart more magnetic power to a bar of their own size, when employed in this peculiar mode, than a single magnet of five times the strength of the former, when applied after the manner of the single touch. The operation of the two poles of the conjoined parcels of magnets on those portions of the bars over which they pass will readily be understood from what has been said with respect to the methods of Knight and Duhamel. They act by the sum of their inductive powers on those parts of the bar that are situated between them, but with the difference of those powers on all those parts which lie beyond them; and the former is therefore always greatly more efficient than the latter. The superiority is the more considerable in the present case, inasmuch as the magnets are nearer to each other, and therefore act with much greater power when they co-operate, but are nearly inefficient when they oppose one another. The latter of these forces, therefore, will never have sufficient energy to destroy, or even much diminish, the effect which had been produced by the former; and thus the magnetism of each portion receives continual accessions of strength every time the magnets are made to pass over it. The long line of bars operates in a manner similar to the pieces of soft iron at the extremities of those in the parallelogram of Duhamel—that is, the external bars act as armatures to those which lie between them; and hence may be understood why these intermediate bars receive the strongest impregnation.

(190.) The different processes for communicating magnetism which we have now described, comprise all those methods that are essentially different in their principle; all others which have been proposed may be regarded as varieties merely in the combinations of which these principles are susceptible. We shall only, therefore, notice those which have been most in repute.

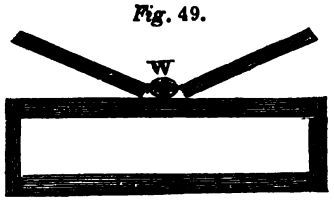
(191.) Mr. Canton published, in 1751, a method which he considered as superior to any of those previously employed. He placed the bars intended to be magnetized so as to form a parallelogram with connecting bars or armatures of soft iron, as in the method of Duhamel. He then had recourse to the method of double touch as prescribed by Mitchell; after which he separated the two bundles of magnets, and inclining them to the bars in contrary directions, as Duhamel had done, he completed the operation by making them slide from the middle towards the extremities. The combination of these two processes was considered by Canton as an improvement upon the method of Mitchell. There is, however, great reason to think, as Coulomb and Biot have remarked, that these successive operations are quite superfluous, and that the bars are left at the end of them precisely in the same state as if only the last had been employed.

§ 8. *Æpinus's Method.*

(192.) Æpinus introduced modifications into the process of the double touch, of greater importance and much more judiciously conceived. He first formed the parallelogram of steel bars in the manner of Duhamel; but in place of the auxiliary cross bars of soft iron, he connected the ends of the steel bars by means of other steel bars which had pre-

viously been rendered powerfully magnetic. He next placed the two compound magnets end to end, with their dissimilar poles adjoining each other, but separated by a small piece of wood (*fig.* 49),

Fig. 49.



which kept them asunder for a short space; and then, inclining them so that they formed a very obtuse angle with each other, he placed them on the middle of one of the steel bars, and, without separating them, made them slide backwards and forwards along the surface of the bar; repeating the operation, with the usual precautions as to the direction of the poles, on the other bar, and on both sides of each.

With regard to the position of the magnets, it is evident that this process is analogous to that of Duhamel; but as the magnets, during the whole time they are rubbed upon the bars, are kept in the same relative situation with respect to each other, their operation depends upon the principle of the double touch peculiar to Mitchell's process. Æpinus tried different angles of inclination for the magnets, with a view to discover that which gave the greatest effect; and concluded that the maximum of effect was obtained when the magnets made angles of fifteen or twenty degrees on each side with the steel bar on which they were to act.

(193.) When an inquiry was instituted as to the comparative efficacy of the methods of Duhamel and of Æpinus, the latter was found to possess this advantage—that it enabled the experimenter to magnetize bars of considerable length and thickness by means of bars which themselves possess no great power, which was not the case with the process of Duhamel. At the same time the method of Æpinus is liable to many inconveniences; in the first place, we scarcely ever obtain, by its means, an equal degree of magnetic power in the two ends of the bars to which it is applied. This will appear by placing any one of these bars on a table, and laying on it a sheet of paper, on which are strewed some very fine iron filings; when it will be seen, by the manner in which the filings arrange themselves that the neutral point of the bar does not occupy the exact middle of the bar, but is sensibly nearer to that end to which the magnets used in the operation of touching it had been last applied.

In the second place, magnets formed by the process of Æpinus are much more liable to have consecutive poles than those obtained by Duhamel's process; and this is especially the case if the magnets are of some length. These consecutive poles, which are irregularly formed in various parts of the magnet, are, it is true, in general extremely feeble; but still they must always impair very considerably the directive force, which becomes a very serious objection when the magnets are intended for compass-needles. The inequality of strength or of diffusion of the two principal poles is also disadvantageous with a view to the same object. Hence the process of Duhamel will always be found preferable for the construction of compass-needles; while that of Æpinus is more serviceable when it is wished to obtain a very considerable magnetic power in large bars, for the purpose of batteries, or other magnetic combinations, where it imports little whether the neutral points be exactly coincident with the centres of each individual piece.

§ 9. *Coulomb's Process.*

(194) The attention of M. Coulomb, already distinguished by his researches in electricity, was engaged for a considerable period in perfecting the art of making magnets; and his numerous communications to the French Academy and Institute contain a great mass of valuable observations on this subject. Some of the results of his experiments are given by Biot, in his "Traité de Physique."*

(195.) The magnetic apparatus for impregnating a steel bar consists, as we have seen, of two parts; the first is that which is fixed, and applied to the bars in such a manner as to act by its continued inductive operation; this includes the armatures of soft iron, as well as the fixed magnets that may be substituted for them: and the second is the moveable magnetic bars, or combinations of bars, which are made to slide and rub over the bar to be magnetized. For the construction of the fixed part of the apparatus, Coulomb employed bars of

* Tome iii. p. 57.

steel tempered at a cherry-red heat, and from twenty to twenty-four inches in length, of rather more than half an inch in breadth, and one-fifth of an inch in thickness. These he first magnetized to saturation by means of other magnets procured by any of the methods already described; then, placing them parallel to each other, and uniting them by their poles of the same denomination, he arranged them into two assemblages, composed of five bars in each, separated by small parallelopipeds of soft iron, which projected a little beyond their extremities, and performed the office of an armature, common to the whole set (see *fig.* 50).

Fig. 50.

The moveable part of the apparatus he usually formed of four bars of steel, tempered at the same heat as the preceding, and of the same dimensions as to breadth and thickness, but only sixteen inches long. After magnetizing them as strongly as possible, he united two of them by their widths, and two others by their thicknesses, forming a packet consisting of four magnets placed as close as possible.

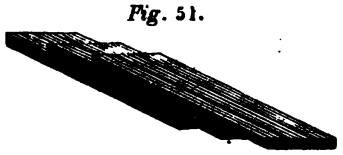
(196.) In proceeding to operate with this apparatus, the large assemblages of magnets, with their armatures, are placed opposite to each other; so that the magnets which compose them shall lie in the same line, with their north and south poles opposite to each other, but separated by a space nearly equal to the length of the bar to be magnetized, which latter bar is to be laid between the two sets of magnets, resting on the cross bars or armatures, for the space of about the fifth of an inch. Then the moveable magnets are laid upon the centre of the bar, and inclined on each side in opposite directions, so as to form with each half of the bar an angle of twenty or thirty degrees.

Every thing being thus prepared, it is at the option of the experimenter to proceed according to the manner of Duhamel, by drawing each packet of the moveable magnets away from the middle of the bar, along that half of it which lies on its own side, as far as the extremity; or, following the directions of Æpinus, to retain the magnets in their relative situation, by placing between them a piece of wood or of copper, so as to keep their poles at an invariable distance of one quarter or one fifth of an inch from each other, and preserving their inclinations, to slide them backwards and forwards from the centre to each extremity of the bar, until each half of it shall have been subjected to an equal number of frictions. After the last movement has been completed, when the magnets will have been brought back to the centre, where the movement had commenced, they are to be raised perpendicularly to a height sufficient to obviate all sensible disturbance of the magnetic state of the bar, and the operation repeated on its other side.

(197.) If the pieces which compose the moveable magnets have not previously received all the magnetic power of which they are susceptible, as will generally happen if we have not previously the command of a sufficient apparatus for that purpose, their united power, when assembled in the manner already described, will still produce in the bars subjected to their action in the above process, a degree of magnetism greater than that which they themselves possess. We may therefore avail ourselves of the latter of these bars for composing a new set of magnets, which will accordingly be more powerful than the former: and then, obtaining by their means still more highly impregnated magnets, we may again disunite them, and subject them to the action of still more energetic combinations, formed by the bars last impregnated. By the continued repetition of these processes, employing one set of magnetic bars alternately in raising the intensity of those of another set, it is evident that we shall finally succeed in effecting their complete saturation.

(198.) When it is required to magnetize bars of very considerable size, Coulomb recommends that the moveable apparatus of magnets should be composed of a much greater number of pieces than in the instance above given; and that these pieces should be disposed in rows, each successive row projecting beyond the last, as shown in *fig.* 51: thus the pole of each, which generally resides at the very extremity of the bar, will

Fig. 51.



come immediately in contact with the bar to be magnetized, when the compound magnet is applied to it with the proper inclination, and the whole will powerfully conspire in producing the same effect.

(199.) The parallelograms of steel bars and soft iron should be kept firm by wedges, in the manner of printers' types, and the extremities of the magnetic bars should be perfectly cleaned. In rubbing the bars, it is recommended by some authors to apply considerable pressure; but Captain Kater found increased pressure rather injurious than beneficial. Dr. Robison conceived that by wetting their extremities he obtained a greater effect; but he found that the least drop of oil between the bars greatly obstructed the operation of the magnets, as was also the case when the smallest piece of the thinnest gold leaf intervened. He found that bars which were rough received a more powerful magnetism than those which were moderately polished; but that, if moderately rough, they acquired the first degrees of magnetism more expeditiously than smooth bars, but did not ultimately receive so strong an impregnation as the latter.

§ 10. *Comparative Advantages of the different Processes.*

(200.) An account of Coulomb's experiments on the comparative advantages of the different methods of magnetizing bars of different thicknesses, lengths, and forms, is given by Biot in his "Traité de Physique." The strength of each magnet was estimated by the number of oscillations which it performed in a given time on each side of the magnetic meridian by the influence of terrestrial magnetism. The following are some of the results of his inquiry.

He found that steel wires of small diameter may be rendered magnetic to an equal degree, whether touched by the method of Duhamel or of Æpinus, or even when simply rubbed with the single pole of a strong magnet, for in all these cases they became magnetized to saturation. When a plate of unannealed steel of greater width than the wires, but of equal length and thickness, was subjected to experiment, a slight difference was perceptible in the degree of magnetism resulting from the different methods, those of Duhamel and Æpinus being the most efficacious. The difference was more perceptible when the steel was made of a harder temper, and increased still more when thicker plates of steel were tried. The processes of Duhamel and of Æpinus, when applied to plates of which the thickness is less than one twelfth of an inch were nearly of equal power; but when they exceed this thickness, that of Æpinus was decidedly the most efficacious. In the case of bars sixteen inches long, one inch broad, and about one third of an inch thick, the comparative intensities of the magnetism produced by the methods of Æpinus and Duhamel were nearly in the proportion of nine to eight.

(201.) Captain Kater also made a series of valuable experiments on the effects of different methods of magnetizing, and on the influence of extent of surface, independently of the mass, on the directive force.* The directive force was estimated by means of the balance of torsion of Coulomb. This instrument consists of a fine wire terminated above by an index at right angles to it, which is moveable round a circle divided into degrees. To the lower end of the wire a cradle is attached for receiving the needle which is the subject of experiment. The instrument being adjusted so that the needle was in the magnetic meridian when the wire had no torsion, the index was turned, and the wire consequently twisted, until the needle was made to deviate 60° from its original position. The number of degrees passed over by the index would then be the measure of the directive force of the needle.

The needles to be magnetized were right-angled parallelograms, five inches long; the one seven-tenths of an inch broad, and the other of half this breadth. The broadest was reduced in thickness till it was of the same weight as the other, namely, one hundred and forty-two grains. The magnets employed were first placed perpendicularly on the centre of the needle, their opposite poles being joined; their lower extremities were then separated and kept asunder by placing between them a piece of wood a quarter of an inch thick, their upper extremities remaining in contact.

* Philosophical Transactions for 1821, p. 104

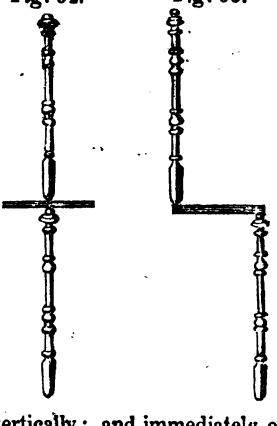
The magnets were then slid along the needle backwards and forwards from end to end, and this was repeated on both sides, till it was conceived that the full effect had been produced; and the directive force of the magnet thus obtained was noted. The process was repeated with the same apparatus, excepting that the magnets were separated at the top by a piece of wood of the same thickness as that at the bottom. The effect was considerably diminished by this change. When the lower extremities of the needle were separated by a piece of wood to the distance of half the length of the needle, the upper extremities remaining in contact, the effect was greater than in the first experiment. A further augmentation of power was obtained when the magnets were joined and placed perpendicularly, as before, on the centre of the needle, and then moved in opposite directions from the centre to the extremities, keeping each magnet perpendicular to the needle; afterwards rejoining them at a distance from the needle, replacing them on its centre, and thus continuing the operation. The needles were then magnetized according to the method of Duhamel, the magnets being inclined at an angle of about forty-five degrees, and carried as before from the centre to the ends of the needle. This was attended with a still greater increase of effect; but it was increased still further when the magnets formed with the needle an angle of about twenty degrees. The maximum of effect took place when this angle was reduced to about two or three degrees; for when the magnets were laid flat on the surface of the needles, and drawn from the centre to the ends, the effect was not so great as in the last case.

(202.) On the whole, Captain Kater concludes that the best mode of communicating magnetism to a needle, is by placing it in the magnetic meridian, joining the opposite poles of a pair of bar magnets (the magnets being in the same line), and laying the magnets so joined, flat upon the needle with their poles upon its centre; then having elevated the distant extremities of the magnets, so that they may form an angle of about two or three degrees with the needle, they are to be drawn from the centre of the needle to the extremities, carefully preserving the same inclination; and having joined the poles of the magnets at a distance from the needle, the operation is to be repeated ten or twelve times on each surface.

(203.) We have seen (§ 171), that terrestrial magnetism may be made available for procuring artificial magnets by the help of percussion; and it now remains that we point out the methods of employing it, in the absence of all other magnetized bodies, in exciting magnetism by friction, either by the single touch or by a method analogous to that of Dr. Knight.

(204.) Let the needle to be magnetized be placed horizontally in the magnetic meridian and fixed in that situation, and apply to the middle of it the lower end of a long iron bar, a poker, for instance,

Fig. 52. *Fig.* 53.



held vertically; and immediately opposite, at the lower side of the needle, apply the upper end of a second bar of a similar description to the first, as seen in *fig.* 52. Then draw each bar, still kept in a vertical position, towards the opposite ends of the needle (*fig.* 53), taking care that the upper bar be drawn towards the side of the needle intended to be its south pole, and the lower bar towards the intended north pole; then, separating the bars, remove them to a distance, and bring them again perpendicularly to the middle of the needle; and repeat this operation a sufficient number of times on each side. This simple process will often, if the needle be small, be sufficient to magnetize it to saturation. The principle on which it is founded is sufficiently obvious.

§ 11. *Canton's Process.*

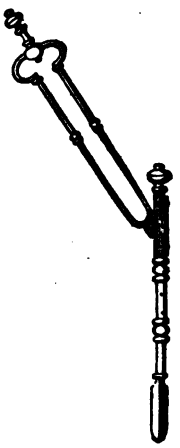
(205.) The process of Canton, already alluded to, proceeds upon the same principle, and does not require the pre-

vious possession of any magnet. As the knowledge of it, therefore, may be of use to those who are not provided with any magnetic apparatus, we shall present the following outline of that part of it which appears to be the really efficient process.

(206.) Six bars of soft steel are to be provided, each three inches long, one quarter of an inch broad, and one twentieth of an inch thick, together with two pieces of iron, each half the length of one of the bars, but of the same breadth and thickness; and also six bars of hard steel, each five inches and a half long, half an inch broad, and three twentieths of an inch thick, together with two pieces of iron of half the length, but the whole breadth and thickness of one of the hard bars. All these bars are to be marked at one end by a line quite round them, in order to distinguish the poles.

(207.) Two bars of iron, or an iron poker and tongs (*fig.* 54), are to be taken:

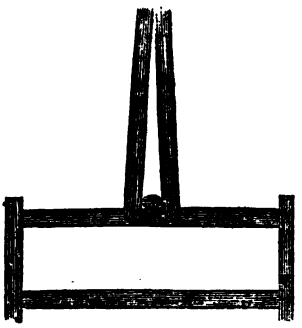
Fig 54.



the larger they are, and the longer they have been used, so much the better. Let the poker be fixed upright, and held by the knees, and let one of the soft steel bars, having its marked end downwards, be tightly fastened to it by a piece of sewing silk, and held with the left hand; then grasping the tongs with the right hand a little below the middle, and holding them in a vertical position, let the bar be rubbed with the lower end, from the bottom to the top, about ten times on each side. This will give it sufficient magnetic power to lift a small key from the marked end, which will, of course, be a north pole.

(208.) Having magnetized four of the soft bars in this manner, the other two (*fig.* 55) are to be laid parallel to each other, at the distance of about one fourth of an inch between the two pieces of iron belonging to them, a north and a south pole against each piece of iron. Two of the four bars that have been already made magnetical are then to be united, so as to make a double bar in thickness, the north pole of one even with the south pole of the other; and the remaining two being placed next to these, one on each side, so as to have two north and two south poles together, the north and south poles are to be separated at one end by a large pin put between them; they are then to be

Fig. 55.



placed perpendicularly with that end downwards, on the middle of one of the parallel bars—the two north poles towards that end intended to be made the south pole, and the two south poles towards the intended north poles. Next slide them backwards and forwards three or four times the whole length of the bar, and removing them from the middle of this bar, place them on the middle of the other bar as before directed, and go over that in the same manner. Then turn both the bars the other side upwards, and repeat the operation.

Having done this, remove the two bars from between the pieces of iron, and placing the two outermost of the touching bars in their stead, let the other two be the outermost of the four to touch these with. This process being repeated till each pair of bars have been touched three or four times over, they will thus acquire a considerable magnetic power.

Next put together the six bars, as was done with the four, and touch

with them two pair of the hard bars, placed between their iron armatures, at the distance of about half an inch from one another. The soft bars may now be laid aside, and two of the hard bars, placed between their iron armatures, may be magnetized by means of the other four, which should be held apart at the lower end, at an interval of about one fifth of an inch; to which distance they are to be separated after they are set on the parallel bar, and brought together again after they are taken off. The same process as that above described is now to be continued until each pair has been touched two or three times over.

The whole of this process may be gone through in less than half an hour; and each of the larger bars, if they had been previously well hardened, may be made to lift twenty-eight troy ounces, or even more. Bars thus impregnated will give to a hard bar of the same size its full virtue in less than two minutes; and may, therefore, answer almost every purpose in natural philosophy much better than the natural loadstone, which has seldom sufficient power to impregnate hard bars.

§ 12. *Horse-shoe Magnets.*

(209.) Magnets in the form of a straight bar are less convenient when the action of both the poles is wanted, as happens in various experiments, especially such as concern the raising of weights by the force of magnetic attraction. In order to bring the two poles near each other, artificial magnets are often made in the shape of a horse-shoe, (*fig.* 56,) or sometimes a more semicircu

Fig. 56.

Fig. 57.

ar form is given to them (*fig.* 57). These horse-shoe magnets, as they are called, may be rendered magnetic by the same process as a straight bar; the magnets by which they are rubbed being, of course, made to follow the curvature of the bar. The method of Æpinus is best suited for the communication of magnetism to bars of this shape.

(210.) Horse-shoe magnets, that have their poles brought very near to each other, are exceedingly convenient as substitutes for the compound magnets employed in the process of magnetizing by the double touch. They fulfil, indeed, all the purposes of compound magnets in this operation; and if placed at once on the middle of the needle to be magnetized, with the poles turned in a direction the reverse of that of the poles intended to be given to the needle, and then moved backwards and forwards along the surface of the needle, taking care to pass over each half of it an equal number of times, and repeating the same operation on the other side, the needle is speedily and effectually rendered magnetic. The readiness with which this may be put in practice, and the absence of all previous preparation, are strong recommendations in favour of this form of magnet.

(211.) Powerful magnetic batteries are sometimes constructed by uniting a number of horse-shoe magnets, laying them one over the other with all their poles similarly disposed, and fastening them firmly together in a leathern or copper case.

§ 13. *Preservation of Magnets.*

(212.) From what has been already said respecting those circumstances which tend to produce or to destroy magnetism, we may easily devise rules for the preservation of magnets, for, unless kept with care, and with the observance of certain precautions, they soon lose their power.

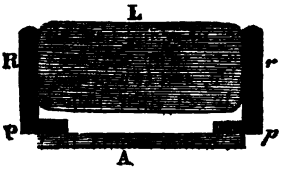
(213.) If a single magnet be kept in an improper position, that is, one differing much from that which it would assume in consequence of the action of terrestrial magnetism, in process of time it becomes gradually weaker; and this deterioration is most accelerated when its poles have a position the reverse of the natural one. Under these circumstances, indeed, unless the magnet be made of the hardest steel, it will in no long time lose the whole of its magnetic power. Two magnets may also very much weaken each other if they be kept, even for a short time, with their similar poles fronting each other. The polarity of the weaker magnet, especially, is rapidly impaired, and sometimes is found to be

actually reversed. More frequently, however, there arises, from this opposition of powers, considerable irregularity and confusion in the poles of both magnets. Heat, as we have seen, impairs magnetism; care should therefore be taken to avoid exposing magnets to a high temperature. We should likewise be very cautious to avoid all rough and violent treatment of a magnet; for we have seen how quickly its virtue is lost by any concussion or vibration among its particles. A fall on the floor, especially if it strike against any hard substance, will materially weaken it: rubbing with coarse powders, for the purpose of polishing it, and grinding, in order to bring it to any required form, are equally injurious. A natural loadstone will, in like manner, suffer by such an operation; hence we should attempt to alter its natural form as little as possible; and when it is necessary to do so, it should be effected very rapidly by cutting it briskly in the thin discs of a lapidary's wheel.

(214.) Although the loadstone retains its magnetic virtue more tenaciously than any artificial magnet that can be constructed, yet even this body requires a certain management for the permanent preservation of its power. For this purpose it should be *armed*, as it is called; that is, an armature of iron should be applied to both its poles. In order to do this most effectually, we must first ascertain the situation of the poles of the loadstone; and cutting off all the superfluous parts, give it the shape of a parallelopiped, having the poles in the middle of two opposite surfaces, and at the same time taking care to preserve the axis, which passes through the poles, of as great a length as can be obtained: for it has been observed, that any curtailment of the magnet in the direction of this line deprives it of force in a greater degree than when shortened in any other direction.

(215.) Two plates of very soft iron must next be provided, equal in breadth to the surfaces containing the poles, and a little longer than those surfaces; so that, when applied to them, a portion of each plate shall project beyond the loadstone to a small extent. In *fig.* 58, R *r* represents the sections of these iron plates affixed to the opposite sides of the loadstone L; and P *p* the projecting pieces. These projecting pieces should be much narrower than the other portion of the plates. For loadstones weighing less than an ounce, the lower surfaces

Fig. 58.



of the projections need not exceed the tenth of an inch; and so in proportion for larger loadstones. The thickness of the plates, also, must be regulated by the strength of the loadstone, and can scarcely be determined without previous trial in each particular case. The best way, therefore, is to make them tolerably thick at first; and then file off successive layers, until we find, by actual experiment on the power of the loadstone after each reduction, that we cease to obtain any advantage; for the power increases gradually to a certain limit, at which the filing ought to be discontinued. The armature of a loadstone should be fixed on it very firmly, by wires, or by an external case, which should be made of any metal which is not susceptible of magnetism. Loadstones are sometimes cut into a spherical shape, in imitation of the earth, and are then called *terrellæ*. Their armatures should, in that case, be adapted to the curvature of the surface, and should each cover about a quarter of that surface.

(216.) The addition of armatures to a loadstone is found to have a very favourable effect in augmenting its strength, and this increase of strength goes on for a considerable time after they have been applied. But there is another, and a still more important advantage resulting from them, in enabling us to direct the power of the loadstone, and to concentrate it into a small space. The polarities of loadstones are often diffused over a considerable part of their surface; and these scattered forces could never be made to bear upon any point on which they are required to act, unless by the intermedium of some substance which might collect and unite them. The iron armatures supply this intermedium. They receive at their expanded part the inductive influence of all the scattered poles residing in the surfaces to which they are applied; and this influence being transferred to the narrow extremity, is there concentrated, and acts with full effect. By this expedient also, the resultant forces, derived from each

single pole, are brought near to each other, and their directions rendered parallel: they are, therefore, made to conspire in various actions which require the joint operation of both poles, such as that of eliciting magnetism by the double touch. The same advantages, indeed, are procured by this construction as we have already seen obtain in the case of horse-shoe magnets when compared with straight magnetic bars. Thus we find that a loadstone which, in the natural state, would appear to be exceedingly feeble, will possess, when properly armed, very considerable magnetic powers.

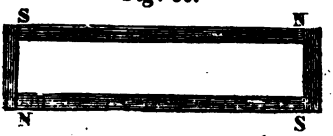
(217.) The armature of a loadstone not only contributes to exalt its magnetic virtue, but also furnishes us with the means of preserving it uninjured. Its two poles, being now transferred to the extremities of the armatures, or to each *foot* of the armature, as it has been called, on connecting these poles, by applying to them a bar of soft iron, A (*fig.* 58), we may effectually prevent the dissipation of their magnetism. This cross-bar performs a similar function with relation to these poles that the iron plates do to the loadstone itself—it acts as a secondary armature; and we find, after applying this bar, that the apparatus gradually acquires greater power up to a certain limit. Such therefore is the mode in which loadstones, when not in use, should always be kept, with a view to the preservation of their powers.

(218.) Directions of a similar kind, and derived from the same principles, apply also to the preservation of artificial magnets. Horse-shoe magnets should have a short bar of soft iron (A, *fig.* 59) adapted to connect the two poles, and should never be laid by without having such a piece of iron adhering to them. Bar magnets should be kept in pairs, lying parallel to each other, with their poles turned in contrary directions, and the dissimilar poles on each side connected by a bar of soft iron; so that the whole may form a parallelogram as in *fig.* 60. They should fit into a box when thus arranged, so as to guard against accidental concussions, and to preserve them from the dampness of the atmosphere. Magnets should be polished, not indeed with a view to the increase of their magnetism, but because they are then less liable to contract rust. It is convenient that those ends which have the northern polarity should be marked with a line all round, in order to distinguish the respective poles in each magnet.

Fig. 59.

A

Fig. 60.



Chapter VI.

Magnetic Instruments.

(219.) In every branch of science, the value of a correct theory is best estimated by the extent and importance of its practical applications. The nearer its approach to perfection, the greater the assistance we derive from it in constructing instruments for the accurate measurement of spaces, of times, or of forces, and for the accomplishment of the objects which relate to that particular science. It is thus that in magnetism, if the theory, developed in the preceding part of this treatise, be correct, it ought to furnish principles for the construction and management of magnetic instruments, such as the compass, dipping-needle, &c. Our limits permit us only to point out the leading principles which particularly deserve attention in the case of each kind of instrument.

§ 1. *Of the Compass.*

(220.) The term *compass* is a general name for all instruments calculated to indicate the position of the magnetic meridian, or of objects with reference to that meridian, whether adapted for being used on land, and in the bottoms of mines, where we have a stable support at command, or for observation at sea, where the perpetual agitation of the surface deprives us of that advantage.

The first class, which merely show us the direction of the magnetic meridian, includes the *Land Compass*, the *Mariner's Compass*, and the *Variation Compass;* the second, or those which mark the angular distances of objects from this meridian, are called *Azimuth Compasses.*

(221.) Whatever modifications may be rendered necessary by the particular purpose of the compass, the essential parts of which it consists are the same

in all—namely, a magnetised bar of steel, generally termed *the needle*, having at its centre a cap fitted to it, which is supported on a sharp-pointed pivot fixed in the base of the instrument. In the mariner's compass, the needle is also affixed to a circular plate, or *card*, the circumference of which is divided into degrees, while an inner circle described upon it is marked with the thirty-two points of the compass, or *rhumbs*, as they are called. The pivot of support rises from the bottom of a circular box, which contains the needle and its card, and is covered with a piece of glass,* in order to protect them from dust, and prevent their being disturbed by the agitations of the external air. The compass box is suspended within a larger box, by means of two concentric brass circles, or *gimbals*, as they are called; the outer one being fixed by horizontal pivots, both to the inner circle which carries the compass box, and also to the outer box; and the two sets of axes being in directions at right angles to one another. By the combinations of movements determined by these axes, the inner circle, with the compass box and its contents, always retains a horizontal position, during the rolling of the ship.

(222) The qualities required in the needle of the compass, for the perfect performance of its office, are these:—first, its directive force compared with its weight, or with the mass which that power has to set in motion, should be as great as possible; while, secondly, the impediments to the exertion of that force, and which consist principally in the friction between the cap and pivot, should be as small as possible. Hence it becomes important to consider the relation subsisting between these opposing forces, and to ascertain those conditions which give the greatest preponderance to the directive force.

(223.) The friction that takes place between the pivot and the cap which rests on it, will, in different compasses, bear a certain proportion to the pressure on the points of support, provided these parts are constructed precisely in the same manner in each case. This pressure is proportional to the weight of the needle and the parts which turn with it. Coulomb concluded, from a set of experiments he made with a view to ascertain this particular point, that when the pivots terminate in a sharp point, and the caps are made of very hard materials, the friction is very nearly proportional to the square root of the cube of the weights. But after long use, the point of the pivot becomes blunted, and the surface of contact with the bottom of the cap is considerably enlarged. In this state the friction is found to be simply proportional to the pressure.

(224.) Assuming this, then, to be the law of relation between them, let us take a magnetized needle of any given size and shape, and support it upon a pivot in the usual manner. Let us next place upon it another needle, precisely similar in all its dimensions, and magnetized to the same degree. The pressure on the pivot will now be double what it was before; and therefore the friction, which is proportional to that pressure, will be double also. But the directive force, though increased, will not be twice as great as with the single needle; because, as was formerly shown, the reaction of the similar poles of the two magnets tends to diminish the power of each. Hence the ratio between the directive force and the resistance is diminished, and the compound needle is less sensible to the magnetic influence of the earth, and less fitted for indicating the magnetic points of the compass. The same mode of reasoning applies to any increase of thickness that may be given to the needle. Hence it appears, that when all other conditions are the same, needles of very small thickness possess the greatest sensibility to terrestrial magnetism. To this general proposition there is, however, a limit; inasmuch as excessive thinness in the needle would endanger its bending by its own weight, which would be attended with a considerable loss of power.

(225.) With regard to the most advantageous length for a compass needle, it appears that when we have passed a certain limit, which is about five inches, an increase of length is accompanied by an increase in the directive force in the same proportion; but when the thickness remains the same, the weight, and consequently the friction, increases in

* An electrical state of the glass cover, accidentally excited by friction, has been known to occasion a sensible disturbance of the needle, by attracting its ends. This attraction, when it exists, may be at once destroyed by moistening the surface of the glass. See Phil. Trans. for 1746, p. 242. See also the observations on the local and electrical influences on compasses by Lieutenant Johnson, in the 21st volume of the Quarterly Journal of Science, p. 274.

the very same ratio; no advantage, therefore, as to directive power can be obtained by any increase of length. Beyond the limit just mentioned, therefore, all needles having the same transverse dimensions should, according to theory, be equally sensible, whatever be their lengths. But it is found in practice, that needles which exceed a very moderate length are liable to have several consecutive poles, attended, as we have seen, with a great diminution of directive force. On this account, short needles, made exceedingly hard, are generally preferable.

(226.) The next object of attention in the construction of a compass needle is the shape which is most favourable to the acquisition of the greatest directive power. Various have been the forms given to compass needles; the choice having been regulated more by the whim and fancy of the maker, than by any reference to scientific principles. The forms most frequently met with are the cylindric, the prismatic, that of a rhombus or parallelogram, and that of the flat bar, tapering like an arrow at the extremities. Coulomb, who made many experiments on the subject, gave a decided preference to the last mentioned of these, as being that which, with a given weight of needle, retains the strongest directive force. On the other hand, he found, that any expansion of the needle at its extremities, a form which has sometimes been recommended, is attended with a sensible diminution of power. From the whole of his experiments, he was led to the general conclusion, that in needles of the same form, their directive forces are to each other as their masses.

(227.) This inquiry has been still further pursued by Captain Kater, whose paper in the Philosophical Transactions, already alluded to (§ 201), contains an account of a series of experiments for determining the best kind of steel for a compass needle, and the best form that can be given to it. He found, on comparative trial, that the directive force is little, if at all, influenced by extent of surface, but depends almost entirely on the mass of the needle, when magnetized to saturation. Two needles were prepared of that kind of steel which is called blistered steel, and two of spur steel, each weighing 66 grains. They were of the form of a long ellipse, five inches in length and half an inch in width. One of each kind was pierced, as shown in *fig.* 61; the weight so lost being made up by

Fig. 61.

additional thickness. It is evident that these pierced needles had, though of equal mass, much less extent of surface than those which remained solid. Having formerly had in his possession a compass of extraordinary power, the needle of which was composed of pieces of steel wire put together in the shape of a rhombus, he procured two needles of this form (*fig.* 62), made from a

Fig. 62.

piece of clock spring, which is of that kind of steel called shear steel. In one, the cross piece was of brass; in the other, formed of part of a clock spring. They weighed only 45 grains.

(228.) The results of the inquiry were, that shear steel is capable of receiving the greater magnetic force; and that the pierced rhombus is the best form for a compass needle. Needles of cast steel were also tried, but were found so very inferior, as at once to be rejected. In the same plate of steel, of the size of a few square inches only, portions are found, varying considerably in their capability of receiving magnetism, though not apparently differing in any other respect.

(229.) Captain Kater next endeavoured to determine the effects of various modes of hardening and tempering the needles. He found that hardening a needle throughout considerably diminishes its capacity for magnetism. The greatest directive force was obtained by a needle which was soft in the middle, and its extremities hardened at a red heat. He at first thought that the most effectual means of increasing its retentive power, would be first to soften it throughout, and then harden it at the extremities, instead of first entirely hardening it, and afterwards softening it in the middle. But subsequent experience induced him to attribute the difference of effect to a difference in the degree of heat to which the needle is exposed in softening it in

the middle. Repeated exposure to heat was found considerably to impair the susceptibility of the needle to retain the magnetic power communicated to it; an effect which does not appear to be owing to any decarbonization of the steel. Captain Kater suggests that this deterioration may arise from a permanent expansion produced in the texture of the steel by the repeated application of heat; for the springs of clocks, which was the material used in his experiments, being made by passing the steel through rollers, when it undergoes great compression, it is probable that the state of condensation thus induced is exceedingly favourable to the retention of magnetism.

(230.) The process which, on the whole, he recommends as the most effectual for giving to a needle the greatest susceptibility of directive power, is first to harden it throughout at a red heat, and then to soften it from the middle to within an inch of each extremity, by exposing it to a heat sufficient to cause the blue colour which arises again to disappear.

(231.) The effect of previously polishing the needle to be magnetized was not found by Captain Kater to have any sensible influence on its capacity for receiving directive power. Neither did any advantage result from the employment of increased pressure in applying the magnets over the surfaces of the needle during the process for magnetizing them; but, on the contrary, in one instance it seemed to be attended with a diminution of effect.

(232.) It is an important requisite in a compass needle that its polarities should be concentrated as much as possible in its two extremities, and undisturbed by the action of any consecutive poles existing at intermediate points. We have already had occasion to remark (§ 193) how much the directive force of a needle is impaired by irregularities in the distribution of its magnetism, attended either by a multiplicity of poles, or by an inequality in the strength of the two principal poles. It is on this account that Duhamel's process of magnetizing is so much preferable to that of Æpinus for imparting magnetism to compass needles; being more conducive to uniformity of effect in every portion of the needle. But even with all the care that can be bestowed, we cannot always be certain of obtaining perfect regularity in the disposition of the magnetic power of a steel bar, whatever shape we may give to it, or whatever process we may employ for its magnetization.

(233.) The consequence of the unequal distribution of magnetism on the two sides of the needle, is evidently to produce a deviation of its axis from the true magnetic meridian; and the instrument will therefore fail to point out the real direction of this meridian. There is only one way of discovering the existence and the amount of the deviation proceeding from this cause; it is to reverse the needle, that is, to turn upwards that surface which was before the under surface; and when thus reversed to balance it as nearly as possible in the same point in its axis as that on which it was before supported. If the needle, in this new state of suspension, finally settles in a position somewhat different from that it before assumed, we may conclude that the axis indicated by its figure is not its true magnetic axis; and that the latter, which alone tends to arrange itself in the magnetic meridian, lies in a situation exactly bisecting the two positions assumed by the needle in these two different modes of suspension.

(234.) When compasses are constructed of two separate pieces of steel bars, slightly bent at an obtuse angle in the middle, so as to allow a space for the placing of the brass cap on which it is to be suspended at the centre, and the two pieces joined by their extremities so as to compose a lozenge-shaped combination, they are exceedingly liable to the imperfection just noticed. For, unless the ends of the separate pieces which compose such a needle have been brought, by tempering, to an exactly equal degree of hardness, that side which is the hardest will retain more magnetic power than the other side; and will, consequently, have a stronger tendency to place itself in the magnetic meridian. The needle will, accordingly, incline on the side which favours this tendency, and the line joining its extremities, and which must be regarded as the axis of its figure, will deviate from the magnetic meridian. This evil will have a tendency to increase by time: for the stronger magnetism of one side, will tend first to impair, and at length destroy, or even finally to reverse, the polarities of the parts on the other side to which they are adjacent.

(235.) The mode in which compass

needles are to be suspended, is well deserving of attention. In order to provide a concave surface, by which the needle may rest on the pivot which is to support it, such, that the point of suspension may be just above the centre of gravity, it is generally necessary, in the straight needle, to make a perforation in its centre, and to rivet into the hole a piece of hammered brass, the lower side of which has been hollowed into a conical cavity, while its upper convex surface is allowed to project a little above the level of the upper surface of the needle. It is found, however, that brass is not capable of being rendered sufficiently hard to resist the continued action of the point against which it rubs in every motion of the compass. In process of time it is worn into an irregular hole, giving rise to great friction, and loss of mobility in the compass. This defect is usually remedied by inserting in the upper part of the brass, a piece of polished agate, ground concave, with a decided centre. The best compasses, made for nautical use, are thus furnished with agate caps.

(236.) Some have considered the perforation of the needle at the centre, for the purpose of suspension, as prejudicial to the regularity of the magnetic power, and as tending to the creation of an additional number of poles. But, in reality, the derangement occasioned by the perforation of a magnetic bar at the point of neutrality, is not found to be attended with any sensible inconveniences in practice*. If the shape given to the needle be that of the pierced rhombus, as recommended by Captain Kater, no such objection will arise, since the cross-bar which connected the obtuse angles of the rhombus has nothing to do with the magnetism of the steel bars forming the sides of the parallelogram. It would, no doubt, be easy to balance a straight bar, without removing any part of its substance, by the addition of a rim of copper, or other non-magnetic substance, to the circumference of the card, so that the centre of gravity of the moveable part of the instrument may be brought sufficiently low to be under the point of suspension. But a little reflection will show that more would be lost than gained by this expedient; for every addition that is made to the weight of the parts which have to move along with the needle, lessens the efficacy of the magnetic force which gives them motion, and the friction also, being augmented in the same proportion, conspires to diminish the freedom of the motion of the needle, and to impair its sensibility.

(237.) The best precaution to be taken for ensuring the steadiness of the movements of the compass, under all circumstances, is to balance the needle accurately upon its centre, before the card is applied. Care should be taken that the card is uniform throughout in its thickness and texture, and be perforated with a circular hole in its centre, so that when united to the needle, the equilibrium of the whole may be perfectly preserved. In order to fix it to the needle, the latter is tapped with two small screw-holes, at the distance of about half an inch from each end; and the card being placed so that the meridian line marked on it is in the same vertical plane with the axis of the needle, and holes being made in it opposite to those in the needle, small screws are introduced, so as firmly to fasten them together. In order to secure the steadiness of the compass during the violent and irregular movements to which the ship is liable, the suspension of the box by the gimbals should be made with great care; the several axes of motion being so adjusted as that the point of suspension on which the needle, with its card, is supported, be exactly in the same line with both these axes.

(238.) Complaints are frequently made by seamen, that, in a rough sea, the ordinary compasses are so unsteady as to prevent their being easily observed; an inconvenience, which they are apt to ascribe to the needle's being too strongly magnetic, and therefore too easily disturbed by the irregularities in the motion of the vessel. This supposed defect they endeavour to remedy by adding a weight to the card: and this is often done, very injudiciously, by loading it with sealing-wax. Sometimes they stick a few pieces of paper on the under side of the card, to serve as vanes which, acting upon the air, may create a resistance to the oscillations of the needle. It has even been proposed, with a similar design, to make the needle move in oil, or other liquid, keeping it still suspended, as usual, on its pivot—the fluid serving to check the vibrations. But all these expedients, calculated to diminish the mobility of the needle, by counteracting the opera-

* Coulomb, Mémoires de Mathématique et de Physique presentés à l'Académie. Tom. ix., 1780.

tion of its directive force, are productive of an evil of a much more serious kind, than any that can arise from mere unsteadiness: for it is evident that the very same cause which makes the compass partake of the irregular motions of the ship, forces it, in the same degree, to deviate from its proper position in the magnetic meridian. While the card remains apparently steady, the steersman will pursue his course, unsuspicious of danger, until the first warning of his error may, perhaps, be the sudden appearance of a shore, from which he had imagined himself at a considerable distance. The real remedy for the inconvenient vacillations of the compass is that we have already pointed out, namely, the accurate adjustment of the point of suspension in the line of the axis of rotation of the gimbals, which, as we have before observed, ought to intersect one another at right angles, in that same point. In addition to this, it may be advantageous to increase the weight of the magnet, provided its directive force be at the same time augmented. This may be effected by employing, as the compass needle, a magnet of greater thickness, or by combining several needles together, laying them parallel to one another; for if both the magnetic power and the weight, (and consequently the friction,) increase in the same proportion, the directive power will remain the same as before; and the compass, thus constructed, being heavier, will be deranged to a less extent by the same disturbing force; and when deranged, will be brought back by the directive force to its proper bearing, with the same facility as in an instrument of the ordinary construction.

(239.) It is to be recollected that if a needle, in its unmagnetic state, be so constructed as that it shall be accurately balanced when resting on a point at its centre, and shall maintain itself in a horizontal position, and if it be afterwards magnetized, the influence of terrestial magnetism will cause it to assume an inclined position, one of its ends preponderating, as if it had acquired additional weight. In order, therefore, to restore the equilibrium, and bring it back to the horizontal plane, it will be necessary to add a corresponding weight to the other end of the needle.

The degree of inclination in the unbalanced needle, depends upon the amount of the dip, which, as we have seen, varies in different parts of the world, according to the situation of the place with regard to the magnetic poles of the earth. Hence, when the compass is transported to a distant part of the globe, a different adjustment must be made of the weight applied to correct the tendency to dip. These adjustments are best effected by means of a sliding piece of brass placed under the needle, and the position of which may change, according to circumstances, on the one side or the other, to any distance that may be necessary In long voyages, during which the changes of latitude are considerable, the position of this regulating weight requires to be frequently shifted, in order to accommodate the needle to the varying changes of inclination incident to the variations of latitude.

(240.) The Azimuth Compass differs from the ordinary Mariner's Compass only in the circumference of its inner box being provided with sights, through which any object, either in the horizon, or above it, may be seen, and its bearings from the magnetic points of the compass determined, by reference to the position of the card, with respect to the sights. For this purpose the whole box is hung in detached gimbals, which turn on a strong vertical pin, fixed below the box, which is thus capable of being moved round horizontally, and of the sights being directed to whatever object is to be viewed through them. On one side of the box there is usually inserted a nut or stop; which, when pushed in, presses against the card and stops it; this is done to enable the observer to read off the number of degrees of the card, which correspond with an index, or perpendicular line, drawn in the inside of the box. They are also sometimes read off by means of a wire stretching from one sight to the other across the centre of the card.

(241.) Analogous to this instrument is the land or surveying-compass, which is also furnished with sights, and means for reading off the degrees on the card. This latter object is effected in a very ingenious manner, by a contrivance of Mr. Schmalcalder, for which he procured a patent. The card is balanced in the usual manner, and contained in a round brass box, with two sights, the one to which the eye is applied being furnished with a triangular prismatic lens, and the other being an open sight, with a vertical horse-hair line extending along its middle.

The pupil of the eye being bisected by the upper edge of the prism, as in the Camera Lucida, the object and that part of the circumference of the card on which the degrees are marked, are seen at the same time; the former by direct vision, the latter by reflexion from the internal surface of the inclined face of the prism: and thus the coincidence of the two may be accurately noted. A prism of the same kind is also applied in Gilbert's patent Azimuth Compass.

(242.) The Variation Compass, designed to exhibit the diurnal changes of variation in the horizontal magnetic needle, has generally a needle of much greater length, than those of other kinds of compasses; and as it is not required to move round the whole circumference, the box, instead of being circular, is oblong, so as to admit of a deviation of only 20 or 25 degrees from the middle line. A vernier scale, with a magnifier, is usually applied in order to estimate the changes of position of the needle with greater precision.

§ 2. *Of the Local Attraction of Vessels.*

(243.) The indications of the mariner's compass at sea are liable to error from a cause which, till lately, had never been supposed capable of affecting the needle. It consists in the attraction which the large quantity of iron, contained in various parts of the ship, exerts upon the magnetic needle: for although the action of each individual piece of iron may, at the distance at which it is placed, be quite insensible; yet the united action of the whole quantity dispersed in every part of the vessel, may amount to a considerable sum, and occasion a very perceptible deviation of the compass from its true position in the magnetic meridian. This will happen more especially in ships of war, which contain a large number of guns, of iron-shot, and of water-tanks, and various parts of the frame-work of the ship which are now made of iron.

(244.) If we suppose each particle of iron to exert a certain attractive force upon the magnetic poles of the compass needle, according to a certain law, hereafter to be determined, it is easy to understand how the combined effect of all these forces may be considered as equivalent to one simple resultant force acting in a certain direction. If the quantity of iron be considered as equally distributed on both sides of the ship, and the compass be placed, as is usual, in the binnacle, in the after part of the ship, this resultant force, which represents the combined action of the iron, will be situated in a vertical plane passing through the compass, and through the axis of the ship, and will, moreover, have a certain inclination to the horizon. In the northern regions of the globe, the inductive influence of the earth on unmagnetic iron consists in carrying the southern polarity upwards, and the northern polarity downwards, (§ 107,) in a direction parallel to that of the dipping needle. The action on the compass of a piece of iron thus brought into a state of induction will, therefore, be precisely similar to that of a magnet having the position of the dipping needle, and placed at a considerable distance from the compass. If it be placed, with relation to the compass, exactly in the magnetic meridian, (that is, to the magnetic north or south of the compass,) it can have no effect in disturbing its position. This will generally be the case when the course of the ship coincides with the magnetic meridian, and the needle of the compass is in the direction of the axis of the ship. But if the ship's head be turned to the eastward, and the resultant force of the iron in the ship be directed in a line downwards from the compass, that force will be represented by a magnet placed in the same oblique line; and the south pole of that magnet, being uppermost, will act with most power, and will attract the north pole of the compass needle, causing it to deviate towards the east. The same magnet, placed to the westward of the compass, which would correspond with the ship's head being turned to the west, would occasion a westerly deviation of the compass needle. In the southern hemisphere, when the inductive influence of the earth has a contrary direction, the opposite effects would result from the action of the iron in the ship; for the action would then be represented by a magnet, having a position with respect to its poles, the reverse of what it had in the former case.

(245.) The earliest record of any observation of the effect of this local attraction of vessels, occurs in the voyages of Captain Cook; but the reason of the deviation of the needle does not appear to have been suspected. The first distinct statement of the real cause of this anomaly is contained in a report from

Mr. Downie, Master of H. M. S. Glory, in which there is the following passage: —'I am convinced that the quantity and vicinity of iron in most ships have an effect in attracting the needle; for it is found by experience that the needle will not always point in the same direction when placed in different parts of the ship. Also, it is rarely found that two ships steering in the same course, by their respective compasses, will go exactly parallel to each other; yet these compasses, when compared on board the same ship, will agree exactly *.'

(246.) The next observations on this subject were those of Captain Flinders †, who, whilst surveying the south coast of New Holland, in H. M. S. Investigator, in 1801 and 1802, remarked considerable differences in the direction of the magnetic needle, when there was no other apparent cause for them, than the differences in the direction of the ship's head. This occasioned much perplexity in laying down the bearings, as it was very difficult to find the proper allowances to be made for this deviation of the compass in estimating them. With a view of trying how far an alteration in the disposition of the iron might tend to remedy this source of error, Captain Flinders first removed two guns, which had stood near the compass, into the hold, and afterwards fixed the surveying compass exactly a-midships upon the binnacle; for at first it was occasionally shifted to the weather-side as the ships went about; but neither of these two arrangements produced any material effect in preventing the deviations of the compass. When the ship's head was to the east, the deviation was westward; and the contrary, when the ship's head was to the west: when it was nearly north or south, no deviation was perceptible. These differences, arising from a change in the direction of the ship with regard to the points of the compass, were less considerable as he proceeded to lower latitudes; and on approaching the line of no variation, upon the south coast of New Holland, the deviations of the compass were smaller than either before or afterwards. In reasoning on the cause of these deviations, he supposes 'the attractive power of the different bodies in the ship, which are capable of effecting the compass, to be collected into something like a focal point, or centre of gravity; and that this point is nearly in the centre of the ship, where the shot are deposited, for here the greatest quantity of iron is collected together.' He further supposes that this point is endowed with the same kind of attraction as the pole of the hemisphere where the ship is; consequently, in New Holland, the south end of the needle would be attracted by it, and the north end repelled. On this hypothesis, which appears to be the true one, he explains the phenomena he had observed, and also deduces from it as a necessary consequence, that the deviations of the compass, arising from the attraction of the iron in the ship, must, when the ship is on the north side of the magnetic equator, be directly the reverse of those he had observed in the southern hemisphere; that is, the north end of the needle would be attracted, and the south end repelled. This theory was confirmed by other observations, made in the same ship, in the British Channel.

(247.) The observations of Captain Flinders excited considerable attention at the time they were published; and a course of experiments was, in consequence, made, by order of the Admiralty, in various ships in the Nore. It was found that, in every ship a compass would vary considerably in its position on being removed from one part of the ship to another. Although the general fact was completely established by these experiments, they did not then lead to any further investigation, until the subject was again brought into notice by Mr. Bain, who, in a useful treatise which he published on the Variation of the Compass, placed in a striking point of view the fatal consequences which might attend this source of error. The attention of the public was also particularly drawn to the subject at this time, in consequence of the proposed expeditions to the Arctic regions, from which it was expected that much important information would result with regard to terrestrial magnetism. The local attraction of the vessels sent out on these expeditions was made a particular object of inquiry; and the results of the numerous experiments made for that purpose, are detailed by Captains Ross and Parry in their accounts of their respective voyages; and also by Captain Sabine, in a paper in the Philosophical Transactions *. It is

* Walker's Treatise on Magnetism, published in 1794; quoted by Mr. Barlow in his Essay on Magnetic Attractions.

† Philosophical Transactions for 1805, p. 196

* For 1819, p. 112.

stated by the last of these observers that, in the Isabella and Alexander, the binnacle compasses of the two ships were soon found to differ very materially from one another, in indicating the course steered. The difference was frequently one point, or eleven degrees and a quarter. No dependence whatever could be placed on the agreement of compasses in different parts of the ships, or, of the same compass with itself, if removed but a few inches. Even in the neighbourhood of the binnacles, the variation, as observed amidships, was from 8° to 10° greater than the result of azimuths taken by a compass placed between two and three feet on the larboard side, and an equal difference, in a contrary direction, took place, on removing the compass to the starboard side; all of which introduced great difficulties in the ship's reckoning.

(248.) An extensive investigation of the subject was now instituted by Mr. Barlow, with a view of discovering some principle of computation, or other method, for correcting this source of error, in all parts of the world. The results of the first experiments he made for this purpose, were published by him in 1820*; and, in 1824, there appeared a second and greatly extended edition of the same work, developing the mathematical principles which regulate the action of unmagnetic iron upon a magnetized needle. His situation, as Professor of the Royal Military Academy of Woolwich, gave him the means of pursuing his experiments upon a very extended scale; as he could procure, with facility, considerable masses of iron, such as balls and shells of every denomination, and having that regularity of figure which was most favourable to the application of mathematical formulæ. As the inquiry is important, not merely from its application to the subject of the local attraction of vessels, but also in its bearings on the whole theory of magnetism, we shall briefly state the principal results which he obtained.

(249.) Mr. Barlow ascertained, that a ball of iron produces no disturbance of the compass needle, when the latter is situated in any part of a plane passing through the centre of the ball, and at right angles to the direction of the dipping needle, in the place where the experiment is made. The angle of the inclination of this plane to the horizon is, therefore, the complement to the angle of the dip. In London, where the latter may be taken at 70°, this angle is consequently 20°. The section of this *plane of neutrality*, as it may be called, by a horizontal plane, passing through the centre of the ball, will be a line directed to the magnetic east and west. If a hollow sphere, of considerable diameter, be supposed to extend around the ball, and to be concentric with it, the plane above defined will, by its intersection with the sphere, form a great circle, which may be regarded as the *magnetic equator* of that sphere, with relation to the magnetic action of the ball.

(250.) Another plane of neutrality is constituted by a vertical plane, also passing through the common centre of the ball and sphere, and including the magnetic direction, that is, the line of the dip: this plane is evidently that of the magnetic meridian; and it also intersects a great circle on the imaginary sphere.

We have termed these two planes the planes of neutrality, in preference to adopting the name of *planes of no attraction*, by which Mr. Barlow has designated them, because, as Poisson has remarked, it is not the whole of the attractive force exerted by the iron ball that vanishes in these planes; but only that part of this force which occasions deviations in the natural position of the needle, which, indeed, is the only force of which we are now studying the effects. Strictly speaking, however, there remains another force, acting in a direction parallel to the dipping-needle, but of an opposite nature to the action of the earth, and tending, therefore, to retard the oscillations of the needle. There is, indeed, no plane in which the attraction of a sphere, or, in general, of any body magnetized by the earth's influence, becomes evanescent.

(251.) In like manner, other meridional great circles may be conceived on the sphere cutting the equator at right angles, and meeting at the two poles of that equator; and the situation of any point at the surface of the sphere, may be designated by its distance from the equator, measured on the meridional circle which passes through the point, and which may be defined its *magnetic latitude;* together with its distance from any one meridian, fixed upon as the first meridian, measured on a smaller circle

* Under the title of 'An Essay on Magnetic Attractions.'

parallel to the equator, and passing through the point in question, which distance might be termed its *magnetic longitude*. Mr. Barlow assumes as his first meridian, the circle which passes from the pole to the magnetic east and west points of the horizontal plane instead of the vertical meridional plane.—We cannot help thinking, however, that the multiplication of these planes would have been better avoided, by assuming the latter, necessarily referred to on so many occasions, as the first meridian.

(252.) Having settled these definitions, the law of action deducible from the experimental investigation of Mr. Barlow, may be very simply expressed. The amount of the angular deviation of a compass needle, the motion of which is limited to a horizontal plane, from the true magnetic meridian, at any point on the surface of the sphere, is such, that the tangent of the angle of deviation is directly proportional to the rectangle of the sine and cosine of the latitude of that point multiplied into the cosine of its longitude. As it is extremely convenient to express propositions of this kind in the concise and perspicuous language of algebra, we shall present the above proposition in that form; denoting the angle of deviation by the symbol Δ; the latitude by λ; the longitude by l. The formula will then be as follows,

$$\tan. \Delta = \sin. \lambda \cos. \lambda \sin. l.$$

But since the product of the sine and cosine of an angle is equivalent to the sine of twice that angle, the formula admits of this simplification, and it will then be,

$$\tan. \Delta = \sin. 2\lambda \cos. l.$$

(253.) The results of a numerous series of experiments made by Mr. Barlow, when the centre of the compass was placed in every variety of position, with respect to an iron ball, approximated so closely to those which were given by computation from the above formula, that no doubt can remain of the accuracy of the law from which it is deduced. They have been further verified by Mr. Christie, by a somewhat different method of procedure, of which he has given an account in the Transactions of the Cambridge Philosophical Society *.

(254.) The next object of inquiry was the law of attraction, with relation to distance; and the result at which Mr. Barlow arrived was, that, when the position, with regard to latitude and longitude, remains the same, the tangents of the angles of deviation are reciprocally proportional to the cubes of the distances. Now as it has been established, that the magnetic force varies inversely as the square of the distance, it will follow, that the square of the tangent of deviation is directly as the cube of the force; or, that the tangent of deviation is directly proportional to the $\frac{3}{2}$ power of the force. In order to convert this proportionality into an equation, it is necessary to introduce a certain constant co-efficient for the number expressing the distance. This co-efficient, when the distance is estimated in inches, Mr. Barlow finds to be .00080382. If this be called A, and the distance denoted by d, the formula, comprising all the variable quantities in one equation, becomes,

$$\tan. \Delta = \frac{\sin. 2\lambda \cos. l}{A\, d^3}$$

(255.) The influence of the mass, and also of the surface with relation to the mass, of the iron sphere in modifying its action, were next made the subjects of investigation. Having at first employed solid balls, weighing, respectively, 288 and 128 pounds, the results appeared to lead to the conclusion, that the tangents of the deviations were proportional to the cubes of the diameter, that is, directly as the masses. But when similar experiments were made with hollow shells, of the same diameter as the former balls, Mr. Barlow was not a little surprised to find that no difference was perceptible between the results of these and of the former trials. Hence he concluded, that the power of attraction was independent of the mass, and resided wholly in the surface of the metal; and all subsequent experiments confirmed the accuracy of this conclusion. The inference he drew was expressed in the following proposition, namely, that the tangents of the deviation are proportional to the cubes of the diameters, or to the square root of the cube of the surfaces, whatever may be the weight or thickness of the sphere. Subsequent experience, however, taught him that this law is subject to a limitation in respect to the thickness of the metal in which the magnetic power resides; for if that thickness, be less than the thirtieth of an inch, the power is not fully developed, and its action is diminished.

This conclusion has been since verified by Captain Kater who found, on

* Vol. i. p. 147.

employing three cylinders of iron, the one being solid, and the other two hollow, but all equal in surface, that the deviation of the compass needle, occasioned by the attraction of soft iron, depends on the extent of surface of the iron, and is wholly independent of the mass; excepting a certain thickness, amounting to about two-tenths of an inch, which is requisite for the full development of its attractive energy *. It may be remarked, by the way, that the circumstance of the effective power being limited to the surfaces of bodies, or nearly so, is another striking instance of the analogy which subsists between the magnetic and the electric agencies. These inductive results of observation are all in strict conformity with the theoretical deductions of Poisson already adverted to, § 163.

Introducing into the general formula this new variable quantity, namely, the diameter, or radius, of the sphere of iron, which we shall express by r: it becomes

$$\tan. \Delta = \frac{r^3 \sin. 2\lambda \cos. l.}{A d^3}$$

(256.) These rules and formulæ are capable of being applied in another manner; for, instead of conceiving the imaginary sphere to surround the iron ball, we may imagine a similar sphere concentric with the point of suspension of the needle; and it will then be obvious that the centre of the ball will have the same relative position in the latter sphere, as the pivot of the compass has with respect to the former; so that the reference may be made indifferently to either: and when the mass of iron is irregular, which is the more usual case, it will be more convenient to refer the common centre of attraction of the iron to an imaginary sphere circumscribing the compass.

(257.) It must be observed, however, that in every instrument a limit exists within which the above law ceases to obtain. This limit arises from the influence which the inductive power of the needle may exert upon the iron presented to it; for we have already seen that the consequence of this induction is attraction of the adjacent pole of the magnet, whichever pole that may happen to be. Hence it follows that when the compass is brought so near to the iron, as to act upon it by induction, the laws above determined are superseded by those dependent on this latter cause, and are therefore no longer applicable. In all the experiments made by Mr. Barlow, care was taken that the distances should be such as to be entirely exempt from this disturbing cause.

(258.) Having established the law of action on the compass, as far as regards masses of iron of regular geometric forms, the next object was to determine whether the same law obtains with masses of irregular shapes. This would evidently not be the case, if the popular notion were true, that the poles of a piece of iron, under the influence of terrestrial induction, reside exclusively at the opposite extremities of the mass; whereas if the entire action admits of being referred to one common centre of attraction, in the same manner as the combined effect of the gravitation of all the particles of a body of irregular figure may be considered as directed on a single point, known by the name of the centre of gravity, it is reasonable to expect that the same laws are common to both. Experiments tried, with this view, upon a twenty-four pounder, showed the existence of a plane of neutrality in the most irregularly-shaped masses of iron, and completely established the identity of the operation of the attractive and repulsive forces in all cases, whether the iron was presented in isolated masses, or dispersed in every variety of situation throughout the ship.

(259.) The actual amount of deviation produced in the ship's compass by its local attraction, will, of course, be different in different vessels. With an easterly or westerly course, it has been observed in these latitudes to vary from five to twelve or fourteen degrees: it is of greater amount as the ship is in higher latitudes; and diminishes, without however vanishing, at the equator; and again increases as we approach the south pole. Mr. Barlow, in a paper lately published in the 'Philosophical Transactions *,' gives the following table of the deviation observed in different ships, on the best authorities, from which a general idea may be formed of the extent of error that may thus arise, and also of its average amount.

* Philosophical Transactions for 1819, p. 129.

For 1831, p. 217.

Ship.	Commander.	Place.	Local Attraction.
Conway . .	Capt. Basil Hall	Portsmouth	4° 32′
Leven . . .	Capt. Owen . .	Northfleet	6 7
Barracouta	Capt. Cutfield .	Do.	14 30
Hecla . . .	Capt. Sir E. Parry	Do.	7 27
Fury . . .	Capt. Hopner . .	Do.	6 22
Griper . . .	Capt. Clavering .	Nore , .	13 26
Adventure .	Capt. King . . .	Plymouth	7 48
Gloucester .	Capt. Stuart . .	Channel .	9 30

giving a mean of 8° 44′ at the east and west points in these latitudes.

(260.) The last of these ships, the Gloucester, was reported as being 'invariably drawn, in consequence of this deviation, to the southward of her intended place, notwithstanding the greatest care being taken in steering her.' Had it not been ascertained, by taking an observation, that this error was altogether the effect of local attraction, it would probably have been ascribed to the influence of an unknown current. The real deviation, estimated in distance, would occasion the vessel, after running ten miles, to be more than a mile and a half to the southward of her reckoning; and so on in proportion as the distance increased. An error of this magnitude, occurring in a narrow channel and in a dark night, were it unknown or disregarded, might lead to the most disastrous consequences. The wreck of his Majesty's ship Thetis, which lately happened on the coast of Brazil, has been ascribed, with some probability, to a mistake of this kind. The following is the account given of this accident in the 'United Service Journal:'—'The Thetis sailed from Rio Janeiro on the 4th of December, with a million of dollars on board, besides other treasure, and every prospect of a fine passage, stretching away to the south-east. The next day, the wind coming rather favourable, they tacked, thinking themselves clear of land; and so confident were they, that the topmast studding-sails were ordered to be set, the ship running at the rate of nine knots; and the first intimation they had of being near land, was the jib-boom striking against a high perpendicular cliff, when the bowsprit broke short off, the shock sending all three masts over the side; thus in a moment bringing utter destruction on this fine vessel and her valuable cargo.' Mr. Barlow shows, in the paper above referred to, that the deviation of the compass, arising from the attraction of the vessel, was exactly of the kind that was likely to occasion this great mistake in the ship's reckoning: for the distance run by the Thetis being about eighty miles, if the local attraction of the vessel had been equal to that of the Gloucester, she would have passed five miles nearer to Cape Frio than had been calculated upon; an error quite sufficient to account for the fatal catastrophe.

(261.) It is obvious that, when the cargo of the ship consists chiefly of iron, the error in the reckoning may be even more considerable than what has been now stated. The most fatal consequences might arise in a few hours to a vessel in the Channel, under these circumstances, in a dark and blowing night, having for its only guide a compass, subject to an error of fourteen degrees in opposite directions at east and west, the very courses on which she would be endeavouring to steer. How many of the mysterious wrecks that have taken place in the Channel might not be traced to this cause! The loss of the Thames Indiaman is given as an example by Mr. Barlow*. This vessel, besides the usual appointments of guns, &c., had a cargo of more than four hundred tons of iron and steel. The influence of such an enormous magnetic mass would alone be quite sufficient to explain the otherwise unaccountable circumstance, that after leaving Beachey-head in sight at six o'clock in the evening, the ship was wrecked upon the same spot between one and two o'clock in the morning, without the least apprehension of being near the shore.

(262.) The practical application of the principles above established to the correction of the actual deviations of the compass in a ship, being, as we have seen, of such great importance in navigation, Mr. Barlow bent his mind to the discovery of a method of effecting so desirable an object. His first idea was, that since the guns and other iron of a vessel must produce exactly the same deviation of the needle as a smaller mass of iron placed in a similar situation, but as much nearer as its mass is smaller, it might be possible to place such a body of iron aft of the compass, as would exactly counterbalance the action of the guns, &c., forward, and consequently leave the needle as free to move, as if no such action existed: but he soon found that, for this purpose, the position of the compensating ball of iron would require to be

* Essay on Magnetic Attractions, p. 367.

shifted for every different position of the ship, which would, of course, be impracticable. He therefore had recourse to the following expedient, which was found to answer perfectly under all circumstances of situation. Since it is possible to place a ball of iron in the same line of direction, with regard to the compass, as that in which the combined action of the iron of the ship is exerted, and to bring it to the exact distance at which its action shall be equal to that of the ship's iron, it is obvious that a ball so placed will, instead of destroying the deviation of the compass, double its amount; and that this will be the case under all circumstances, and in every part of the world. Instead, therefore, of fixing the ball, let its proper place be first determined, and the ball itself laid aside; then, at any time when it is desirable to ascertain what effect is due to the magnetic attraction of the ship, let it be applied in the situation so determined, and observe how many degrees it draws the needle of the compass from the direction it had previously to the application of the ball. This will be the amount of the actual deviation produced by the iron of the ship; and the correction in the course of the vessel may be applied accordingly. Strictly speaking, it is not the angle of deviation which is doubled by the action of the ball, but the tangent of that angle; but as, in small angles, the tangents are very nearly in the ratio of their arcs, they may in most cases be taken, without sensible error, as the same.

(263.) As the effect to be obtained depends on the surface, and not on the mass of the iron which acts, Mr. Barlow has found it more expedient to employ plates of iron, instead of balls. The form he recommends is a double plate, composed of two thin plates of iron, screwed together in such a manner as to combine any strong irregular power of one plate, with a corresponding weak part of another; by which means a more uniform action is obtained. These plates are of a circular form, twelve or thirteen inches in diameter, with a hole in their centre, through which is passed a brass socket, with an exterior screw; a brass nut, about an inch and a half in diameter, screws on the exterior of each end of the socket, thereby pressing the plates together; with an interposed thin circular piece of board, which is intended to increase in some degree the thickness of the plate, without adding to its weight. It would appear also that the compound plate is more powerful when the two, of which it is formed, are thus separated from each other *. The proper position of the plate, with regard to the compass, must be ascertained by trials on shore; comparing its effects, in different relative situations, with the observed deviation of the compass on board the ship.

(264.) Although the method proposed by Mr. Barlow be exceedingly ingenious, and will, no doubt, to a certain extent, prove highly useful, several causes exist in practice which must interfere with the regularity of its operation. Changes of temperature will probably affect the compass-needle, the compensating plates, and the large masses of iron contained in the ship, in very different degrees; and many of the latter bodies will be more or less susceptible of acquiring permanent magnetism in the different circumstances in which they are placed. In the course of a long voyage, extending to very different latitudes, these causes are liable to considerable variation, and must introduce a degree of uncertainty in the amount of the changes induced. Still, however, the method of Mr. Barlow will furnish a most valuable approximation to the correct determination of the influence which the ship exerts on the needle of the compass. Certain it is that the proper estimate of the disturbing force arising from this cause has, of late years, acquired increased importance from the very large proportion of iron now employed in the construction of ships of war, and of the machinery for their guidance. Independently of the guns, shot, and iron water-tanks, the knees of the ship, the capstans, and cables are now made of iron, so that the whole forms a very large and powerful magnetic mass.

(265.) In all situations, but more especially in high magnetic latitudes, experience has shown the advantage of adopting an expedient originally suggested by Captain Flinders: namely, the selection of some particular spot in the ship as the permanent position of a standard compass, in which it should be invariably placed for use, whether in observing azimuths, or bearings of land, or in directing the ship's course: so that if, on any particular occasion, it

* Barlow's Essay on Magnetic Attractions. Second edition, p. 100.

should be necessary to use a compass in any other part of the ship, a reference should be made to the standard of comparison, and the difference, if any, in its pointing noted and allowed for; a certain degree of uniformity being found to obtain in the effects of the local attraction on a compass thus confined to one spot, enabling a navigator to form a sufficiently correct judgment of the different amounts of variation to be allowed with it on each change in the direction of the ship's head *.

(266.) Not only are the compasses on ship-board disturbed by the magnetic attraction excited by the iron existing in the vessel; the chronometers also are affected by the same influence. The sudden alteration in the rates of chronometers at sea had been frequently noticed by intelligent seamen, but had been generally ascribed to the motion of the vessels. The true cause was first pointed out by Mr. George Fisher, who accompanied Captain Buchan in his voyage to the Arctic Regions, in the year 1818, and who gave an account of his observations on this subject to the Royal Society †. He found that the chronometers on board the Dorothea and Trent had a different rate of going from what they had on shore, even when these vessels had been frozen in, and therefore when their motion could not have contributed to that variation. It appeared that this effect could be attributed only to the magnetic action exerted by the iron in the ships upon the inner rim of the balance of the chronometers, which is made of steel. A similar influence was perceptible on placing magnets in the neighbourhood of the chronometers. This conclusion was confirmed by the experiments made for this purpose by Mr. Barlow, who ascertained that masses of iron, devoid of all permanent magnetism, occasioned an alteration in the rates of chronometers, placed in different positions in their vicinity. The alterations varied according to the positions of each chronometer with relation to the magnetic equator of the masses of iron to whose influence it was subjected, and was always uniform in the same position. In the case of the chronometers on board the Dorothea and Trent, their rate was always accelerated. Mr. Barlow found, however, that this depends on the circumstances of the case, for in other instances they were retarded. He suggests that great care ought to be taken to keep the chronometers on board of any ship out of the immediate vicinity of any considerable mass or surface of iron. They ought not, for instance, to be kept in the cabins of the gun-room officers, which are on the sides of the vessel; as probably a strong iron knee, or even a gun, will be found at a very inconsiderable distance from the spot where the watch is deposited.

Mr. Barlow proposes to rectify this error by a method similar to that which he employs for the correction in the compass, namely, by previously ascertaining what the effect of the ship's iron is upon the rate of the chronometer. This may be done by means of a box or pedestal, on the top of which is a convenient receptacle for the chronometer, and in the side of which a brass pin is fixed, to carry the compensating double iron plate, employed to represent the action of the ship's iron on the compass. Then, having ascertained the rate of the chronometer in the usual manner, let the rate be again taken while it is placed on the pedestal. The plate should generally be kept at the distance of about a foot from the vertical line, through the centre of the dial; and its centre should be about the same depth below the plane of its balance. The rate thus obtained will be a very close approximation to the ship's rate of the instrument, provided care be taken to keep it out of the immediate action of any partial mass of iron, and to place it in the same direction with respect to the ship's head as it had with respect to the iron plate when its rate was determined *.

§ 3. *Of the Azimuth Compass.*

(267.) The purposes to which the azimuth compass is applied, and the general principles of its construction, have already been stated in § 240; but, for the sake of those who are desirous of making practical use of it, it will be necessary to enter into a fuller detail.

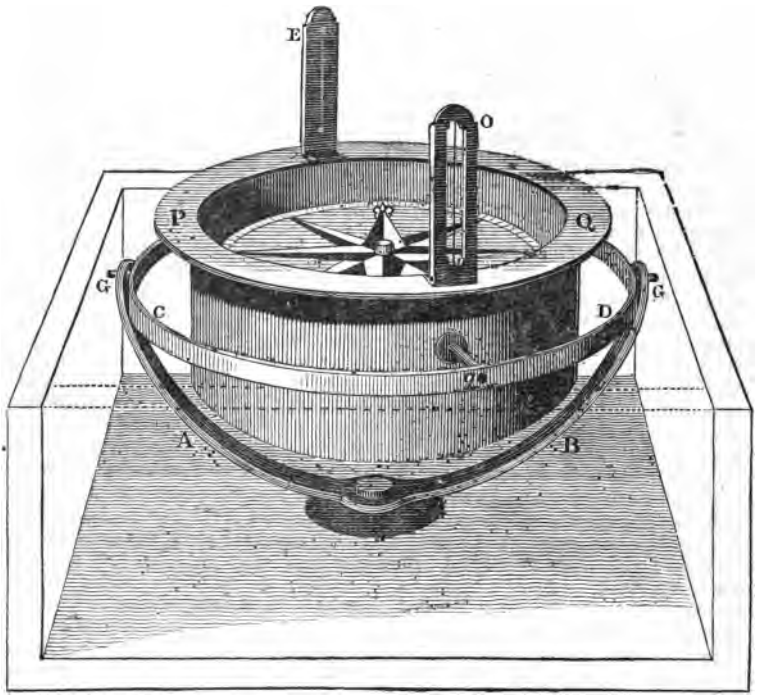
The ordinary azimuth compass is represented in *fig.* 63. The semicircle AB is fixed by a screw at its middle, or lowest point, to a stand at the bottom of the outer box, containing the whole apparatus, in such a manner as to ad-

* Parry's Journal of a Voyage for the Discovery of a North-West Passage, &c., Appendix, p. cxviii.
† Philosophical Transactions for 1820, p. 196.

* Barlow's Essay on Magnetic Attractions, p. 125.

mit of its being turned round horizontally, and placed in all azimuths. To the upper extremities of this semicircle, a brass circle, CD, is fixed by two pivots GG, constituting a horizontal axis of motion; while the inner cylindrical brass box, PQ, containing the compass itself, is attached to the brass

Fig. 63.



circle, CD, by similar pivots, of which one is seen at *g*, forming a horizontal axis at right angles to the former, and both together acting as gimbals. The compass, with its card, is balanced in the usual manner on a pointed pivot rising from the centre of the bottom of the inner box, the upper side of which is covered with a circular piece of glass. The two sights, E and O, are fixed vertically on the upper side of the cylinder of this box, diametrically opposite to each other; the one, E, to which the eye is intended to be applied, consists of a brass slip, having a narrow vertical slit; the other, O, which is turned to the object, is a similar slip, having an oblong aperture containing a fine thread, or horse hair, passing along the middle of the open space in a vertical direction. Two vertical lines are also marked on the inside of the box, which are prolongations of the slit in the sight for the eye, and of the thread in that for the object. These lines are intended as indexes for the measurement of the angular distance in azimuth of an object viewed through the two sights, from the place of the magnetic meridian, as shown by that portion of the graduated edge of the card, which coincides with the line with which it is compared. The degrees are reckoned from the north point of the compass, which is marked zero, all round the circle, in the direction from left to right, that is from north to east, and thence to south and west.

(268.) Sometimes a wire is placed between the two sights, stretching horizontally from the foot of the one to that of the other. This is intended as an index to ascertain coincidences with the degrees marked on the card, when they are viewed from above: but as this is a mode of using the instrument that is seldom practised, this wire is usually omitted, and observations made solely by means of the vertical lines.

(269.) On one side of the box con-

pass is also well adapted for surveying, for which object, indeed, it was originally invented. To apply it to this purpose, nothing more is necessary than to slide the frame containing the segment of the glass cylinder to the top of the sight, when the hair will be seen, which must be made to bisect the object viewed by direct vision at the moment that its bearing is also read off by reflexion.

(275.) There is also another mode of using this compass, which may, perhaps, be found more convenient and accurate than that already described. It is simply to turn back the reflecting sight, and to view the line of light, and read off the degrees by direct vision; and it has this decided advantage, that if the compass should not be in a horizontal position, the observer may readily perceive and correct the error. Some care, however, is necessary not to mistake in reading the figures indicating the degrees, they being inverted as marked upon the card: this may be prevented by viewing them also by reflexion.

(276.) On approaching the north pole of the earth, the north end of the needle will incline downwards; but the card may again be readily balanced by taking out the ring and glass, and attaching a small bit of wax to the south pole of the needle.

(277.) When it is considered how great is the diminution of the power with which the magnetism of the earth acts upon the horizontal compass needle in very high magnetic latitudes, the satisfactory results which have been obtained, even under such extreme circumstances as those of the late arctic voyages,—in Davis's Straits, for instance, and Baffin's Bay,—from the employment of Captain Kater's azimuth compass, which gave correct observations when other instruments became useless, afford the best testimony of its excellence, and of the precision which may be expected from its employment in the ordinary course of observation*.

(278.) In some azimuth compasses, for which patents have been taken, a triangular glass prism is substituted for the mirror in the above instrument, acting evidently on the same principle of reflexion, and evidently borrowed, with a trifling alteration of form, from the original invention of Captain Kater. Coloured glasses are sometimes provided for making observations on the sun; they are placed so as to be readily interposed between the eye and the nearest sight when wanted, and are removeable at pleasure when not required.

* See Captain Sabine's observations in the Philosophical Transactions for 1819, p. 141.

§ 4. *Of the Variation Compass.*

(279.) A magnetic needle intended to indicate the minute changes that take place in the direction of terrestrial magnetism, should, as already noticed (§ 242), be of somewhat greater length than an ordinary compass, in order that the extent of the variations of angular position may be more conspicuous.

(280.) For the same purpose, the following method was practised by Du Hamel:—At each extremity of a long needle, a slender, pointed piece of steel was erected perpendicularly, which served as sights for observing its position with reference to the divisions of a graduated limb, six feet in length, fixed to a pillar at the distance of nearly sixty feet from the needle, and in the direction of its axis*.

(281.) Analogous to this was the construction employed by Mr. Prony, consisting of a long magnetic bar, on which was fixed a telescope, moving along with it; its motion being observed by looking through it at a distant object, the image of which would have a corresponding motion in the field of the telescope. Humboldt, who made many observations with this instrument, considered it to be a very accurate method.

(282.) But a point of much greater importance is that the magnetism of the needle should be uniform, and that its magnetic axis should remain permanent. Hence its form should be of the simplest kind, such as that of a slender needle of nearly equal diameter throughout, and magnetised with great care. The observation of minute changes of position may be made with sufficient accuracy by means of a magnifying glass; which expedient will supersede the necessity of employing sights, or of giving to the needle any extraordinary length.

(283.) Another material point is to obtain great delicacy of suspension, so that the needle shall immediately obey the slightest change of direction in the force of terrestrial magnetism, or of

* Histoire de l'Académie Royale des Sciences de Paris, for 1772, part ii., p. 50.

† Biot, Traité de Physique, tom. iii., pp. 143, 144.

any other extraneous magnetic force. This object can hardly ever be sufficiently attained by balancing the needle upon a point, as in the common compass; because, however small the friction may be, it is still a force which is required to be overcome at the beginning of every new motion, and which must even prevent all motion until the moving power has increased to a certain amount. This objection does not apply in the same degree to the suspension of the needle by a fine thread, which is accordingly the best plan of construction for a variation compass. Care should, of course, be taken that the force of torsion be as small as possible. Mr. Bennet proposed a spider's thread as the best material for obtaining great delicacy of suspension, and procuring the greatest magnetic sensibility: for although twisted through many thousand turns, it occasioned no sensible deviation in a needle suspended by it; showing that its force of torsion is insensible *.

(284.) The thread should be contained in a vertical tube, fitted to the middle of the upper side of an oblong box, the remaining parts of which are to be completed by glass plates, for the purpose of protecting the needle from agitation by the air. With a graduated arc adapted to each end of the needle, and magnifiers to observe the exact position of the extremities when referred to these arcs, this simple form of the instrument, which is the one employed by Captain Kater, is calculated to answer every practical purpose that can be desired. Its superiority to the ordinary construction was shown on the occasion of the late Northern Expeditions, when it was found that the friction on the metal point in the variation needle belonging to Mr. Browne, made by Dollond, nearly a foot in length, and suspended in the usual manner by an agate cap on a metal point, was, in the high magnetic latitudes reached by Captain Parry, too considerable to be overcome by the directive power of the magnet; and accordingly it happened that at Winter Harbour the instrument was quite useless, while the one furnished by Captain Kater still traversed †.

(285.) Considerable light, however, may be thrown upon the causes that produce the minute diurnal or monthly changes in the variation, by adopting the expedient suggested by Mr. Barlow, and which we have already slightly alluded to, § 122. From a variety of considerations, we are warranted in concluding that the direction assumed by the magnetic needle is the result of a great number of magnetic forces acting upon it, some of which are of a nature more permanent than the rest. Thus, while the average direction is the resultant of some cause of very general operation, affecting extensive portions of the globe, many occasional changes are effected by causes of a more transient nature, some of which are periodical in their influence, but of which others are, as it were, accidental, or at least very irregular and fluctuating in their action. Innumerable observations have proved that the compass-needle is more or less agitated during the prevalence of the aurora borealis *. Its deviation from this cause has been known to amount to six or seven degrees. Volcanic eruptions have been at various times observed to occasion considerable disturbance in the position of the needle: this was particularly noted during the eruptions of Mount Hecla and of Vesuvius†. Atmospherical changes, such as violent winds, or a fall of snow, have, in like manner, been known to affect the needle. The electrical conditions of the atmosphere, and especially those connected with the approach or occurrence of thunder-storms, have a powerful influence on magnetic polarity.

(286.) It is evident that as the needle in its ordinary states is urged to move by a force resulting from the influence of these variable forces, combined with those that are of constant operation, the effect of the former would be much greater if the latter were withdrawn; and this can only be effected by neutralizing the operation of these constant forces. Mr. Barlow effected this by applying one or more magnets in the requisite positions, so as to counteract almost entirely the natural magnetic influence of the earth. In illustration of which he gives the following example ‡. Supposing that a finely suspended hori

* Philosophical Transactions for 1792, p. 81.

† Parry's Journal of a Voyage for the Discovery of a North-West Passage, &c. See Appendix, p. cxvi.

* See Wargentin's Memoir in the Philosophical Transactions for 1751, p. 196.

† The Abbé de la Torre observed changes of several degrees in the declination of the needle, during an eruption of Vesuvius.

‡ Philosophical Transactions for 1823, p. 327.

zontal needle, under the natural influence of the earth, makes one vibration in two seconds; and that by masking the terrestrial influence by magnets properly adjusted, the time of vibration is increased to eight seconds; then it would follow that the directive power was reduced to one-sixteenth of the former; and, consequently, that any lateral magnetic force acting upon the needle would produce an effect sixteen times greater than before; so that if the former were twelve minutes, the new effect on deviation might be expected to amount to between three and four degrees, and therefore be such as to admit of distinct and satisfactory observation. Thus he found that when the needle was kept in its natural position, and then deprived of nearly the whole of its directive power by bringing a magnet near it, the daily variation might be magnified almost to any amount. The same result was obtained when the north pole of the needle was directed to the south, east, or west, or, indeed, any required position, at least within certain limits. With this view, Mr. Barlow first deflected the needle, by the repulsion of a magnet, into a certain position, and then, by means of another magnet, modified its directive power in the same way as when it was in its natural position in the magnetic meridian.

(287.) Thus, by combining different sets of observations, in different positions of the needle, information may be obtained as to the direction as well as intensity of the extraneous forces that interfere with the general directive influence of the earth. Mr. Christie, in prosecuting these investigations, preferred applying two magnets, placed one above and the other below, and on different sides of the needle, in the line of the dip, or that in which it would arrange itself if freely suspended by its centre of gravity, instead of retaining them in the same horizontal plane with the needle, conceiving that a more equable distribution of the forces acting on the needle would thus be obtained; for a portion of the forces acting upon the horizontal needle in the line of these magnets would be destroyed, and it would still be acted upon by forces in the same direction as before, but of less intensity; whereas by even applying the poles of two magnets to the corresponding poles of the needle, and in the same plane with them, the horizontal directive force of the needle would be diminished by increasing the angle which the resultant of the terrestrial forces and those of the magnet made with the horizon, and which would be nearly equivalent to increasing the angle of the dip. This arrangement also procured the further advantage of obtaining various modifications of effect, by altering the distances of the neutralizing magnets from the needle, whereby inferences might be deduced as to the variations in the intensities of the deflecting forces occasioning the deviations of the needle at different times. It would exceed the limits of this treatise to attempt even a short abstract of the mode of investigation pursued by Mr. Christie in this inquiry, and for the details of which we must refer our readers to his paper in the Philosophical Transactions*. The general results to which he arrived have already been given in §§ 123, 124.

(288.) In observations for determining the exact variation, great care should be taken that the compass employed be unaffected by any local causes of attraction from iron in the neighbourhood. In the account given of the meteorological instruments used at the Royal Society's house†, Mr. Cavendish points out the method he employed in order to ascertain whether this cause of error existed; and if so, to determine its amount. He removed the variation compass from the apartments of the Society, into a large garden belonging to a house in Marlborough-street, about a mile and a quarter to the west of Somerset House, where there seemed to be no danger of its being affected by any iron-work. Here it was placed exactly in the meridian, and compared for a few days with a very exact compass, placed in an adjoining room, and kept fixed constantly in the same situation. It was then removed back to the Society's house, and compared again with the same compass. By a mean of these observations, the difference between the position in the two stations was ascertained, indicating the amount of the local influence of the iron in the house and adjacent buildings, and consequently the error of the instrument.

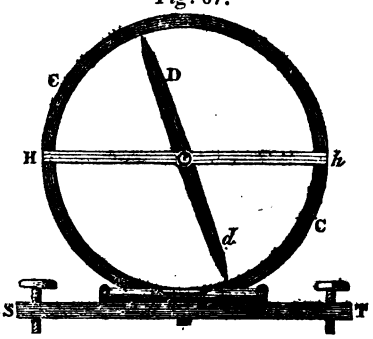
§ 6. *Of the Dipping-Needle.*

(289.) The principle on which the dipping-needle acts has already been

* For 1833, p. 342.
† Philosophical Transactions for 1776, p. 391.

explained (§ 97), as also the general form of the instrument.

Fig. 67.



(290.) The simplest construction is that represented in *fig.* 67. The needle D *d* is a flat oblong piece of steel, broader at the middle, and tapering to a point at the extremities. A slender cylindrical axis is passed at right-angles through its centre, and moves freely in circular apertures made in the middle of the lateral horizontal bars, H *h*, fastened to a vertical graduated circle, CC, indicating the angle which the needle makes with the horizon. This circle is fixed to a flat stand, ST, provided with one or more levels; the horizontality of which is adjusted by means of screws placed at the corners of the stand. The usual mode of observing with such an instrument is first to ascertain the direction of the magnetic meridian by a common compass, and then, removing the compass to a sufficient distance, so that it may not affect the position of the dipping-needle, to fix the circle of the latter in the plane of this meridian, and then to render it perfectly level by means of the screws of the stand. For the adjustment of the instrument in the meridian, in any particular place where the bearing of a distant object is exactly known, the frame containing the needle is occasionally provided with two sight vanes, placed on an index moving horizontally on the top of the vane, and which may be directed to that object.

(291.) Great care should be taken that no iron or steel enters into the construction of any part of the frame-work of the apparatus, as such material might produce a sensible action upon the needle: great attention should even be paid to the purity of brass that may be employed in its construction, and to its exemption from all magnetic properties.

(292.) It was formerly deemed an advantage to make the needles of considerable dimensions so as even to exceed a foot in length. But experience has shown that more is lost than gained in point of accuracy by giving to them a length greater than six or eight inches; and considerable convenience, of course, results from this reduction of size, as the instrument is thus rendered more portable, as well as less expensive.

(293.) With a view to diminish friction, Mr. Mitchell, in the year 1772, proposed that the two ends of the axis of the dipping-needle should be supported on friction-wheels; and two instruments with this improvement were executed for the Board of Longitude by Mr. Nairne. The needles were a foot in length, and the ends of the axes were made of gold alloyed with copper, and the friction-wheels on which they rested were four inches in diameter, these wheels being themselves balanced with great care. The ends of the axes of the friction-wheels were likewise made of an alloy of gold and copper, and moved in small holes made in bell metal; and opposite to the ends of the axes of the needles and of the friction wheels, were placed flat agates, finely polished. Each magnetic needle vibrated in a circle of bell-metal, divided into degrees and half degrees; and a line passing through the middle of the needle to the ends pointed to the divisions. The needles were nearly balanced before they were rendered magnetical; and by an ingenious contrivance of Mr. Mitchell, of a cross fixed on the axes of the needles, on the arms of which were cut very fine screws, to receive small buttons, admitting of being screwed nearer to or farther from the axis, the needles could be adjusted both ways, to a great nicety, after being magnetised, by reversing the poles, and changing the sides of the needle. The frame of the instruments were provided with levels for the horizontal adjustment, after they had been placed in the plane of the magnetic meridian *.

(294.) In a subsequent volume of the Philosophical Transactions †, a dipping-needle is described by Dr. Lorimer, calculated for making observations on the dip at sea, where, from the unsteadiness of the supports, the difficulty of attaining any degree of accuracy is very great. The needle was of the

* Philosophical Transactions for 1772, p. 476.
† For 1775, p. 79.

usual shape and size, and moved vertically on its axis, which had two conical points, slightly supported in two corresponding hemispherical sockets, inserted into the opposite sides of a small upright brass parallelogram, about an inch and a half broad, and six inches high. Into this parallelogram was fixed, at right angles, a slender brass circle, about six inches diameter, silvered and graduated to every half degree, on which the dip is indicated by the needle. This, for the sake of distinction, he called the *circle of magnetic inclination*. This brass parallelogram and, consequently, the circle of inclination, also turned horizontally on two other pivots, the one above and the other below, with corresponding sockets in the parallelogram. These pivots were fixed in a vertical brass circle, of the breadth and thickness of two-tenths of an inch, and of such a diameter as to allow the circle of inclination and the parallelogram to move freely round within it. This second circle he calls *the general meridian*. It was not graduated, but had a small brass weight fixed to the lower part of it, to keep it in a vertical position; and the circle itself was screwed, at right angles, into another circle, of equal internal diameter, of the same thickness, and twice the breadth, which was silvered and graduated on the upper side to every half degree. It represented the horizon: for it swung freely in gimbals, and was, consequently, always horizontal. The whole was contained in a mahogany box, of an octagon shape, with a glass plate at the top, and one on each side for some way down. That part of the frame which contained the glass could be lifted off when requisite. The whole box turned round upon a strong brass centre, fixed in a double plate of mahogany, glued together cross-wise, to prevent its warping or splitting; and this again was supported by three brass feet, frosted so as to prevent their slipping when the vessel rolled considerably. When not wanted for use, it was enclosed in an outer square box, in order to preserve it effectually.

The peculiar advantage of this instrument consists in the freedom which is allowed to the needle of obeying the tendency, impressed upon it by terrestrial magnetism, of placing itself in the line of the dip, in consequence of the power which it has of moving in different planes at right angles to one another. Its position with respect to the respective circles points out also, upon simple inspection, not only the inclination, or dip, but also the magnetic bearings in a horizontal plane. Hence by directing the vertical circle to the sun, or other object in the heavens, the magnetic amplitude of the object is also readily determined. Dr. Lorimer's compass, though exceedingly plausible in theory, presents such difficulties in its practical execution, as can scarcely be overcome by the most exquisite workmanship.

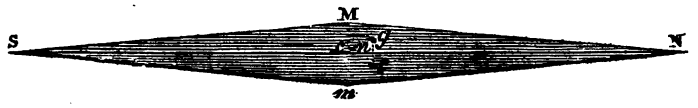
(295.) The dipping-needle formerly used by the Royal Society, and which has been regarded as the model for the construction of instruments of this kind, is described by Mr. Cavendish, in the 66th volume of the 'Philosophical Transactions*.' In this instrument, the ends of the axis roll on horizontal agate planes; and a contrivance is applied, by which the needle may, at pleasure, be lifted off from the planes, and laid down on them again in such a manner as to be supported always by the same points of the axis resting on the same parts of the agate planes, the motion by which it is let down being very gradual and without shake. The general form of the instrument, the size and shape of the needle, and the cross used for balancing it, were the same as in the dipping-needle constructed by Nairne on the plan of Mr. Mitchell, already described, § 293. The mode of using the instrument was as follows: the dip was observed first with its front to the west, and then with its front to the east; after which the poles of the needle were reversed, and the dip observed both ways as before. Care was taken that the needle was rendered equally magnetical after the poles were reversed, as it has been before; this equality being ascertained by counting the number of vibrations made by the needle in a given time in both cases. The mean of these four observations was the true dip.

(296.) In order to estimate the influence of the several causes of error which might singly vitiate the result, but which may be made to compensate one another by combining these different modes of observation; let us suppose *fig.* 68 to present us with a front view of the needle; and S N to be the direction of the magnetic axis, or line according to which its magnetism is exerted; and let

* For the year 1776, p. 375.

M *m* be drawn at right angles to S N, and passing through the centres of the cylindrical ends of the axis, and representing therefore the axis of motion. If the needle were truly balanced, its centre of gravity would coincide with

Fig. 68.



the intersection of these lines at *c*. But supposing this not to the be case, and that in consequence of an error in the suspension the centre of gravity is at *g*; draw *g f* perpendicular to S N, cutting it in *n*, and make *n f* equal to *g n*. When the instrument is turned half way round, so that the opposite face of the needle is presented to us, the edge S M N will now be in the place before occupied by S *m* N, and the centre of gravity will be situated at that part where point *f* was before; therefore the mean between the forces by which the needle is drawn out of its true position in these two situations, in consequence of its not being truly balanced, is accurately the same; and the mean between the two observed dips is very nearly the same as if the centre of gravity had been at *n*. But if the centre of gravity were at *n*, the dip would be very nearly as much too great in the one position of the needle, or it would be too little when the poles are reversed; or *vice versâ*. Therefore the mean of the observed dips in these four situations will be very nearly the same as if the needle were truly balanced.

(297.) In the second place, if the planes on which the axis rolls are not horizontal, the dip will be very nearly as much greater than it would otherwise be, when one face is turned to the west, as it is less when the other is; for if these planes dip towards the south in one case, they will dip as much towards the north in the other, supposing the levels by which the instrument is set to remain unaltered. Consequently, the mean of the two observations will be very nearly the same as if they had been placed in a truly horizontal plane.

(298.) The same method of reasoning will show, in the third place, that the mean of the two observations above-mentioned will not be altered, although the index-line joining the mark by which we observe with the axis of motion be not parallel to the axis of the needle; that is, although the index line do not coincide with the continuation of the line SN; or although the line joining the two divisions of 90° be not perpendicular to the horizon; or although the axis of motion do not pass through the centre of the divided circle, provided it be in the same horizontal plane with it. Should it happen, indeed, that the axis of motion is not in the same horizontal plane with the centre of the divided circle, the error thence arising will not be compensated by this method of observing; unless the position of both ends of the needle be taken as checks upon one another. This, however, is of no consequence, since it is easy to examine whether or not they are in the same horizontal plane.

(299.) But the error that is most difficult to be avoided in the construction of the instrument, is that which arises from the ends of the axis not being truly cylindrical. It is, accordingly, essential that the parts of the axis which rest in the agate planes should be exactly the same. The instrument, however, is so contrived as to admit, on occasion, by giving the axis a little liberty in the notches by which it is lifted up and down, of our making these planes bear against a part of the axis distant about a hundredth or a fiftieth of an inch from their usual point of bearing. Mr. Cavendish found that, when the axis is confined, so as to have no such liberty, and when care is taken, by previously making the needle stand at nearly the right dip, that it shall vibrate in very small arcs when let down on the planes: that then, if the needle be lifted up and down any number of times, it will commonly settle exactly at the same point each time; at least the difference is so small as to be scarcely sensible. But if it be not so confined, there will often be a difference of twenty minutes in the dip, according as different parts of the axis rest on the planes; and that, although the greatest care be taken to free the axis and planes from dust; which can be owing only to some irregularity in the axis. If the needle vibrate in arcs of five degrees, or more,

when let down on the planes, there will frequently be as great an error in the dip. It is true that the part of the agate planes on which the axis rests when the vibrations are stopped, will be a little different, according to the point at which the needle stood before it was let down; which will make a small difference in the dip, as shown by the divided circles, when only one end of the needle is observed, though the real dip, or inclination of the needle to the horizon is not altered; but this difference is far too small to be perceptible; so that the above-mentioned error cannot be owing to this cause. Neither does it seem to arise from any irregularity in the surface of the agate planes, for they were ground and polished with great accuracy; but it most likely proceeds from the axis slipping in the large vibrations, so as to make the agate planes bear against a different part of it from what they would otherwise do. Mr. Cavendish gives it as his opinion that this irregularity is not owing either to want of care or skill in the execution, but to the unavoidable imperfection of this kind of work. He imagines, therefore, that this instrument is at least as exact, if not more so, than any which has yet been made.

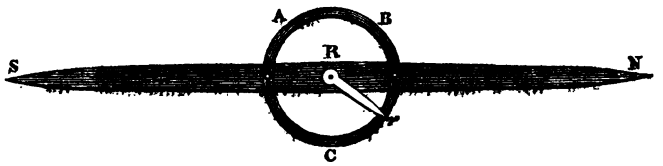
(300.) Thus it appears, that in general the indications afforded by the dipping-needle are liable to two principal sources of error: first, the axis of the magnet's length may not be the exact axis of its magnetic forces; and, secondly, its point of suspension may not, in every position, be exactly coincident with its centre of gravity. Different modes of observation must be resorted to, in order to ascertain the amount of the errors arising from these causes. We must first assure ourselves that the axis of rotation of the needle is perfectly level, so that the needle shall turn in a plane exactly vertical: we must next see that it is placed accurately in the plane of the magnetic meridian; and we have then to observe carefully the positions at which it settles, after being repeatedly disturbed, and allowed to oscillate freely. The mean of these positions may then be taken as the true position of the needle under these circumstances. We are next to turn the whole instrument horizontally till it has described a complete semicircle, or 180°; that face of it which was to the east being now to the west, and *vice versâ*. and then, taking similar observations on the dip, we get a mean of these, for this new position. Comparing these two means, we obtain a resulting mean, which is free from the first source of error. In order to exclude the operation of the second cause of error, we must now remove the needle from its supports, and after destroying its magnetism, magnetize it again in the contrary sense; namely, rendering that end a north pole, which before was south, and *vice versâ*; then, replacing it upon its supports, we must make with it similar sets of observations to those made before, turning it first on one side and then on the other. The mean thus obtained, combined with the former mean, will give the mean of the whole; which may be considered as the true dip, at the place and at the time of observation.

(301.) The error produced by the want of coincidence between the axis of motion and the centre of gravity of the needle may be removed by the following method, devised by Daniel Bernouilli, and which, being easily executed, deserves to be generally known. Let a dipping-needle be constructed with as much correctness as can be effected by the ordinary methods of workmanship, and balanced as exactly as possible before it is rendered magnetic: when impregnated, therefore, it will arrange itself tolerably nearly in the line of dip. Carefully note the position it takes under these circumstances, and then destroy its magnetism. When it has thus returned to its natural state, alter the point of suspension, or adjust the centre of gravity, in such a manner as that it shall arrange itself in the same position as that above noted by the sole influence of gravity. Now impregnate it again, imparting to it the same poles as before. It is evident that it will now approximate still more nearly to the true line of the dip, since nearly the whole of that portion of the force of gravity which before produced a deviation from the position no longer operates. If we find that this approximated position differs several degrees from the former one, the operation may be repeated, until we have arrived so near to the true position, that no further difference can be perceived. It will rarely happen that the third approximation will give an error of half a degree.

(302.) This simple instrument was adapted by its author to observation in all situations, in the following ingenious manner:—A very light brass graduated

circle, ABC, *fig.* 69, is fixed to one side of the needle SN, concentric with its axis, and the whole is balanced as nicely as possible before impregnation. A very light index, R *r*, is then fitted on the axis so as to turn stiffly upon it. This will

Fig. 69.



destroy the equilibrium of the needle. If the needle had been made with perfect accuracy, and perfectly balanced, the addition of this index would cause it always to settle with the index perpendicular to the horizon, whatever degree of the circle it might chance to point at. But as this is not to be expected, the index is to be set at various degrees of the circle, and the position which the unmagnetic needle takes, corresponding to each place of the index, must be observed, and the result of all these observations recorded in a table. Suppose, for example, that when the index is at 50°, the needle inclines 46° from the horizon: if in any place we observe that the needle, rendered magnetic by juxtaposition between two powerful magnets, having the index at 50°, has an inclination at 46°, we may be certain that this is the true dip at that place; for the needle is not deranged by magnetism from the position which gravity alone would give it. As we generally know something of the dip that is to be expected in any place, we must set the index accordingly. If the needle do not show the expected dip, the position of the index must be altered, and the inclination of the needle again observed. Examine whether this second position of the index, and this dip, form a pair which is in the table: if they do, then we have obtained the true dip; if not, we must try another position of the index. Noticing whether the agreement of this last be greater or less than those of the former pair, we learn whether to change the position of the index in the same direction as before, or in the opposite direction. Professor Robison had a dipping-needle of this kind, made by a person totally unacquainted with the making of philosophical instruments. He used it at Leith, at Cronstadt in Russia, at Scarborough, and at New York, and the dip indicated by it did not in any single trial differ a degree and a half from other trials, or from the dip observed by the finest instruments. He tried it in Leith Roads in a rough sea; and did not think it inferior, either in certainty or dispatch, to a needle of the most elaborate construction. Professor Robison deems it worthy of its ingenious author, and of the public notice because it can be made for a moderate expense, and, therefore, may be the means of multiplying observations on the dip, which are of immense value towards perfecting the theory of terrestrial magnetism.

(303.) In a dipping-needle recently made by M. Gambey, at Paris, intended to be used at St. Petersburgh, the axis, instead of being a cylinder, is a knife-edge, as in a fine hydrostatic balance. This edge is placed exactly in the centre of gravity of the whole compound needle, and is so fixed that when the needle dips 71°, the edge rests perpendicularly on two agate plates. It is evident that such a needle, however sensible, is adapted for use only in those situations in which the dip is nearly 71°. It is, however, well calculated for ascertaining minute variations of inclination in the same place *.

(304.) Another mode of dispensing with the condition that the axis of motion should accurately pass through the centre of gravity, a condition which it is next to impossible ever strictly to fulfil, is that adopted in the dipping-needle invented by Professor I. Tobias Mayer, in his treatise, *De Usu accuratiori acus inclinatoriæ Magneticæ* †.

The centres of motion and of gravity are, in this needle, designedly separated, so that the inequalities of workmanship in the axis, or in the planes of suspension, are rendered of less effect, being opposed by the joint influence of gravity and magnetism; whilst, by a peculiar process of observation, and an appro-

* Annales de Chimie et de Physique.

† Published in the Transactions of the Royal Society of Sciences at Göttingen, for 1814.

priate formula, the joint operation of the two forces is resolvable, and the position which the needle should assume from that of magnetism alone is deducible with great precision *. This intentional separation of the centres of gravity and suspension is effected by tapping the needle with a fine interior screw, in order that it may receive a fine steel screw, projecting at some distance from the needle, and on which a small brass ball traverses. By this contrivance, the needle may be deflected from the true dip, in any degree that may be desired, and the terrestrial action, which varies as the sine of the angle of deviation from the line of dip, may be increased in almost any proportion.

(305.) The following is the description of the needle constructed on this principle, which was employed by Captain Sabine in the determinations of the dip, as reported in the work already quoted. This needle was a parallelopipedon of eleven inches and a half in length, four-tenths in breadth, and one-twentieth in thickness; the ends were rounded; and a line marked on the face of the needle, passed through the centre to the extremities, answering the purpose of an index line. The cylindrical axis on which the needle revolved was of bell metal, terminated, when it rested on the agate planes, by cylinders of less diameter; the finer these terminations can be made, as long as they do not bend with the weight of the needle, the more accurate will be the oscillations. Small grooves in the thicker part of the axis received the Y's, which raised and lowered the needle on its supports, and insured that the same parts of the axis rested on the planes in each observation.

A small brass sphere traversed on a steel screw, was inserted in the lower edge of the needle, as nearly as possible in the perpendicular to the index line passing through the axis of motion; by this mechanism, the centre of gravity of the needle, screw, and sphere may be made to fall more or less below the axis of motion, according as the sphere is screwed at a smaller or greater distance from the needle, and according as spheres of greater or less diameter are employed. The object proposed in thus separating the centres of motion and of gravity, was to give to the needle a force, arising from its own weight, to assist that of magnetism in overcoming the inequalities of the axis; and thus to cause the needle to return, after oscillation, with more certainty to the same point of the divided limb than it would do were the centres strictly coincident.

(306.) The centres of motion and of gravity not coinciding, the position which the needle assumes, when placed in the magnetic meridian, is not that of the dip; but the dip is deducible by an easy calculation from observations made with such a needle, according to the fol lowing directions:—

(307.) If the needle has been carefully made, and the screw inserted truly as described, the centres of motion and of gravity will be disposed as in the lever of a balance, where a right line joining them will be a perpendicular to the horizontal passing through its extremities, that is, to the index line. This condition is not, indeed, a necessary one; but it is desirable to secure it, because it shortens the observations, as well as the calculation from whence the dip is deduced. Its fulfilment may be ascertained with great precision, by placing the needle on the agate planes before magnetism is imparted to it, and observing whether it returns to a horizontal direction after oscillation, in each position of the axis; if it do not, it may be made to do so at this time with no great trouble.

(308.) With a needle in which this adjustment can be relied on, two observations made in the magnetic meridian are sufficient for the determination of the dip. The two faces of the needle are in succession turned towards the observer, by reversing the position of the axis on its supports, in such a manner that the edge of the needle which is uppermost in the one observation, becomes lowermost in the other. The angles which the needle makes with the vertical in these two positions being read, the mean of the tangent of those angles is the co-tangent of the dip.

(309.) But when needles are used in which this previous adjustment has not been made, or when its accuracy cannot be relied on, four observations are required; two being those that have been already directed; and the other two being similar to them, but made with the poles of the needles reversed.

Calling, then, the first arcs F and f; and those with the poles reversed G and g, calling the dip δ, and taking

* See Captain Sabine's Account of Experiments to determine the figure of the Earth, p. 467.

tang. F + tang. f = A
tang. F − tang. f = B
tang. G + tang. g = C
tang. G − tang. g = D

Then the dip may be calculated by the following formula:—

$$\frac{A \cdot D}{B+D} + \frac{B \cdot C}{B+D} = 2 \text{ cotang. } \delta.$$

(310.) In reversing the poles, it is not necessary that the magnetic force imparted to the needle should be the same in degree as it possessed previously to the operation. The coincidence of the poles with the extremities of the longitudinal axis may always be insured by adopting the precaution of placing the needle in a groove, to prevent its lateral motion, and by confining the sides of the magnet by parallel strips of wood, so that in moving along the needle they may preserve its direction.

(311.) If the distance between the centres of motion and of gravity be considerable, the arcs in the alternate observations will be on different sides of the vertical, especially when the dip is great; in such cases the arcs to the south of the vertical are read negatively. The arcs in each of the four positions, forming the data from which the dip is deduced, are the arithmetical means of several observations, usually six, half of which should be made with the face towards the east, and half with the face towards the west; the needle being lifted by the Y's and lowered gently on its supports between each observation. The arcs indicated by both ends of the needle should also be read, in order to correct the errors arising from inequality in the divisions, or from the axis of the needle not passing correctly through the centre of the circle.

(312.) In order to insure the perfect horizontality of the agate planes which supported the axis of the dipping-needle on Mayer's construction, employed by Captain Sabine, a spirit level was attached to a circular brass plate, of the proper diameter to be placed upon the planes themselves, with adjustments to bring it parallel to the plate. The errors of the level were shown by placing the plate in various positions horizontally; and the errors of the planes by turning the whole instrument upon its horizontal centre. When these errors were adjusted, and the planes and plate perfectly horizontal the apices of two cones, which proceeded perfectly at right angles from the plate uniting them at their base, and were equal to the diameter of the divided circle of the instrument, ought to have coincided with the divisions 90° and 90° of the circle; when they did not, the cones afforded, in this case also, the means of correcting the adjustment.

(313.) The dipping-needle affords a method of determining the position of the magnetic meridian, independently of the horizontal needle; for if we turn round the whole instrument horizontally (so as to place it successively in different azimuths), till we find that in which the needle assumes an exactly vertical position, the plane of its motion is then exactly at right angles to the magnetic meridian; and the latter may therefore be determined from the former.

(314.) By comparing the inclination of the dipping-needle to the horizon, in two different positions, such that the planes of its rotation are perpendicular to each other, we may, by the following trigonometrical formula, deduce the dip. If the inclinations, observed in the two azimuths, be represented respectively by δ' and δ'', and the dip itself (or the inclination in the magnetic meridian) by δ, then,

$$\text{Cot.}^2\delta = \text{cot.}^2\delta' + \text{cot.}^2\delta''$$

By multiplying observations of this kind in different azimuths, and taking the mean of all, we may arrive at a very accurate determination of the dip.

(315.) Mr. Scoresby has proposed an ingenious method of finding the dip, by observing the situation in which bar-iron, void of permanent magnetism, loses all power of affecting the compass placed at a certain distance from it; for, as Mr. Barlow has ascertained, its position must then be in the plane of the magnetic equator. The inclination of the plane to the horizon is, of course, equal to the complement of the dip. Mr. Scoresby has described an instrument calculated for making this species of observation, in the Transactions of the Royal Society of Edinburgh*.

(316.) Other methods, of a nature somewhat more refined, exist for discovering the dip, which depend on the admeasurement of the intensities of the magnetic forces by which the needle is urged in different positions of the axis and plane of rotation. The magnetic force derived from the influence of the earth, and acting in the direction of the dip, may be resolved into other forces, which will bear to one another the same ratios as the sides of the triangles

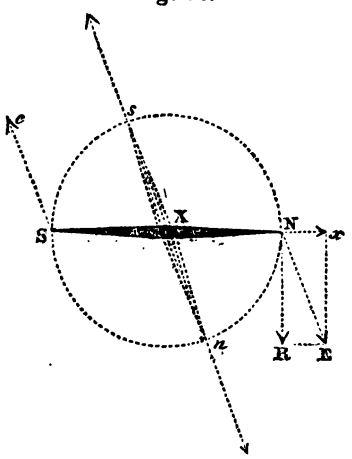
* Vol. ix. p. 247.

which represent them. The angles of these triangles, the dip being one of these angles, may be determined by the trigonometrical relations of these lines when two of them are given. All that is required for this purpose is to ascertain the ratio of the forces which act in directions parallel to these lines, and are proportional to them. Of the methods by which the intensity of these forces is to be measured, we shall proceed to treat in the next section.

§ 6. *Methods of determining the intensities of the Magnetic Forces.*

(317.) When a magnetic needle is moveable in any plane on an axis that passes through its centre of gravity, so that its movements are simply the effects of the magnetic forces of the earth acting upon the two polarities of the needle (which may be considered as concentrated in its poles), it takes a certain position, which is that in which the forces are in equilibrium. Let needle SN, *fig.* 70, for example, be moveable on an axis at X, perpendicular to the plane of the figure; and let

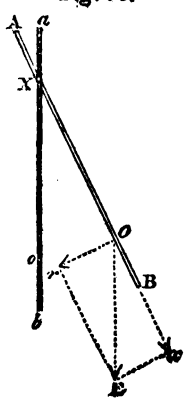
Fig. 70.



NE be the direction in that plane of the force of terrestrial magnetism acting upon the pole N; while S *e*, opposite and parallel to NE, is the direction of the force in the same plane, acting upon the pole S. The position to which the needle is brought by these forces is *s n*, parallel to the common direction of these forces, when they are in direct opposition to each other, and therefore in equilibrium. In order to estimate the rotatory efficiency of the forces in operation in any other position, as SN, we, must resolve the force represented by the line NE into two others; the one, N *x*, in the direction of the radius of rotation XN, prolonged; and the other in the direction NR, perpendicular to it. The force N *x*, being opposed by the fixed axis at X, contributes in no respect to produce motion; NR is the only part of the terrestrial force that turns the needle upon its axis. Now it is evident that NR is to NE, as the sine of the angle NER, or its equal EN*x*, to the radius; but the force represented by the line NE being a constant force, the rotatory force NR will, in every position of the needle, be invariably as the sine of the angle EN*x*, made by the needle, on its prolonged direction, with the direction of the terrestrial force. The same reasoning, in all respects, applies to the force S *e* acting on the pole S; but since it acts on the other side of the axis in a contrary direction, it will concur with the force acting on the pole N, in giving the same rotatory motion to the needle. The effect will, therefore, be equal to the sum of these two rotatory forces, and will be twice as great as either of them taken separately; and the resultant will still be proportional to the sine of the angle of inclination.

(318.) A little consideration will enable us to perceive that the condition of the needle, with regard to the magnetic forces, is analogous to that of a lever moveable on a horizontal axis, and acted upon by the force of gravity. If we suppose a straight lever, AB, *fig.* 71, moveable upon an axis X, at right angles to it, to be raised from the vertical position *a b*, which is that of equilibrium, inasmuch as gravitation acts in

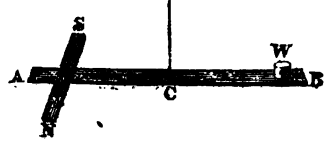
Fig. 71.



that direction, and placed in the inclined position AB, it is well known that the rotatory action of the force of gravity acting upon all its particles is equivalent to a single force acting upon a point, O, which is called the centre of oscillation; and also that, in order to estimate what portion of that force OE contributes to its rotation on its axis, we must resolve it into one in the direction O x, and another in the direction O r, at right angles to it; this latter force being in all cases proportional to the sine of the angle EOx, or its equal BXb. The only difference between this case and the one we have been considering, is that here the force is single, whereas there are two forces acting upon the magnetic poles.

(319.) These two forces being always precisely equal and in opposite directions, perfectly balance one another with reference to any motion of the *whole needle*, either towards or from the earth. This admits of experimental proof; for, in the first place, were there any balance remaining in favour either of the attractive or repulsive forces emanating from the earth, the effect would be shown by an apparent change in the weight of the needle; if, when magnetised, it were on the whole attracted to the earth, it would appear heavier than before; if repelled, lighter. But no such change is observed to take place. Neither is there any tendency manifested in a magnetised bar to a lateral or horizontal motion. This may be proved by placing it at the end of a light frame of wood, AB, *fig.* 72, which is suspended at its centre C by means of a fine silk thread, T; a weight, W,

Fig. 72.



being placed at the other end to act as a counterpoise to the magnet NS. When left to itself, it will be found that the whole apparatus will turn round until the direction of the needle coincides exactly with the plane of the magnetic meridian, just as if it had been suspended by its own centre. Had there existed any force impelling it horizontally, it would have occasioned a deviation from this plane, acting as it must have done with the advantage of the lever AC. But the two equal forces acting differently upon the two magnetic poles, though opposed with respect to any motion of translation, yet concur in their rotatory action, and may, consequently, as far as relates to this action, be regarded as a single force of twice the intensity of either of them taken singly.

(320.) It is evident, then, that the same dynamical laws which regulate the motions of a compound pendulum, actuated by terrestrial gravity, will also regulate those of a magnetic needle, balanced on its centre of gravity, and actuated by terrestrial magnetism. The same pendulum, it is well known, performs all its vibrations in equal times, whatever be the length of the arc in which they are performed, provided that arc be not too great. If we estimate the length of a pendulum by the distance between its centre of motion and its centre of oscillation, then, in pendulums of different lengths, and in situations where the force of gravity is different, the squares of the times of performing a given number of vibrations are directly proportional to the lengths of the pendulums, and inversely proportional to the force of gravity. Now the number of vibrations performed in a given time is inversely as the time employed in each vibration; therefore, the square of the number of vibrations in a given time will be inversely proportional to the length, and directly proportional to the force of gravity.

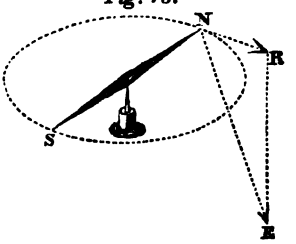
(321.) The same formula being applicable to the vibrations of magnets, a very simple computation will enable us to arrive at an estimate of the comparative forces acting on the same magnet in different inclinations of the axis, and in different situations with respect to the position of equilibrium in the plane of motion. We have only to disturb it slightly from this position, and count the number of vibrations it makes in a given time, a minute for example, in different cases: then, taking the squares of these numbers, they will be proportional to the intensities of the terrestrial magnetic forces that are in operation in these several instances.

(322.) The preceding reasoning is founded upon the supposition that the axis of motion passed accurately through the centre of gravity of the magnet; so that the effect of gravity was removed, and could not in any way interfere with the rotatory force of magnetism. This, however, is a condition, which it is next to impossible practically to fulfil; and if it be not exactly fulfilled, then, whenever the centre of gravity is not in the precise line passing vertically through the centre of suspension, the effect of gravity is to impart to that side of the magnet, on which the centre is found, a tendency to preponderate; and its oscillations are no longer produced by the simple action of the magnetic forces, nor directed to the exact line of their action. The only method of correcting this source of error, when it is not very considerable, is to reverse the polarities of the magnet, and make a new set of observations on the inclination and intensity in this state of the magnet; and then to take the mean of the corresponding observations, which, in consequence of the compensation of the opposite errors existing in the two modes of estimation, will express the true value of the quantity sought.

(323.) In order to compare the results of two sets of observations on magnetic intensity in different parts of the world, it is necessary to employ the same needle in both cases; since the application of the various formulæ necessary to be employed for comparing the action of the same force on two different needles would be attended with great difficulty and uncertainty.

(324.) The oscillations of the compass-needle, which moves in a horizontal plane, furnish data for the calculation of the intensity of that part only of the terrestrial force which acts in that plane; whereas those of the dipping-needle, moving on a horizontal axis and consequently in a vertical plane, when that plane coincides with the magnetic meridian, indicate the full amount of the force of the terrestrial magnetism at the place of observation. The ratio between these two quantities is that of the base and hypothenuse of a right-angled triangle, inclined at an angle equal to the dip; that is to say, the intensity of the horizontal force is to the intensity of the whole force as the cosine of the angle of the dip is to the radius. Let SN, *fig.* 73, be the horizontal needle;

Fig. 73.

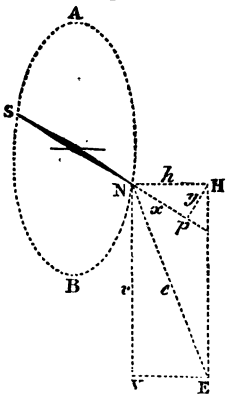


NE the line of dip; NR a horizontal line perpendicular to SN. The force NE is resolved into RE, perpendicular to RN, and which being out of the plane of motion, and perpendicular to it, does not contribute to the motion of the needle, and NR the horizontal force; which latter is to NE as the cosine of the angle ENR is to the radius. This force, NR, is constant in all positions of the needle in the horizontal plane; and acts always in parallel directions. Its rotatory action, however, will, of course, depend upon the deviation of the needle from the position of equilibrium, that is, upon the angle which it makes with the plane of the meridian; being proportional to the sine of that angle. The oscillations are therefore isochronous, that is, performed in equal times, whether the arc be large or small, like those of a pendulum; and are governed by the laws above stated as applying to those of pendulums; and the same remark applies equally to the oscillations of the dipping-needle performed in the plane of the magnetic meridian.

(325.) When the position of the axis of the dipping-needle is changed, so that the plane in which the needle moves is no longer that of the magnetic meridian, though still vertical, the force by which it is actuated is in like manner to be estimated by that portion of the terrestrial force which, on being resolved, has the direction of that plane; that portion which is perpendicular to the plane being of no effect.

Let the circle SANB, *fig.* 74, represent the plane of the motion of the needle SN; NE being the line of dip, or the direction of the terrestrial forces. The force represented by NE may be resolved into the two forces NV and NH, the one perpendicular to the horizon, and the other parallel to it. Let the former be denoted by the letter v, and the latter by h; and let us call the

Fig. 74.



force of the earth e. Let δ be the angle of the dip ENH, and d the complement of that angle, or ENV.

Then by the properties of the triangles NVE, or NEH, we have

$v = e \cos. d$; and $h = e \sin. d$.

(326.) The force v, being vertical, acts wholly in the plane of the needle's motion, SANB: but the force h is out of that plane, and must be decomposed into two others; the one, HP, perpendicular to that vertical plane, and which we shall call y; the other NP, which we shall call x, directed horizontally in that plane. The angle HNP is equal to the deviation of the vertical plane SANB from the magnetic meridian; let us call this angle α.

We shall thus have

$y = h \sin. \alpha$; and $x = h \cos. \alpha$;

or, substituting for h its value as expressed in the former equation, and joining the value of v, we have,

$v = e, \cos. d.$

$y = e, \sin. d. \sin. \alpha.$

$x = e, \sin. d, \cos. \alpha.$

Of these, the force y is destroyed, being resisted by the axis of motion; and the forces v and x are those only which are effective in giving motion to the needle. Let R express the resultant of these forces, and φ the angle which it makes with a vertical line. We shall have

$$R^2 = x^2 + v^2;$$

$$\text{and tang. } \phi = \frac{x}{v},$$

or, substituting for x and v their respective values, as above found,

$$R = e \cos. d \sqrt{1 + \text{tang.}^2 d, \cos.^2 \alpha};$$

$$\text{tang. } \varphi = \text{tang. } d, \cos. \alpha.$$

(327.) From these equations many important consequences may be derived.

In the first place we may deduce, that the intensity of the force R diminishes as the angle α increases; or in other words, as the plane of motion deviates more from that of the magnetic meridian. It is greatest when these planes coincide, being then equal to e; it is least when they are at right angles to one another, for then $\alpha = 90°$, and cos. $\alpha = 0$, whence

$R = e. \cos. d.$

(328.) The direction of the resultant, and consequently the position into which it brings the needle, also vary in the different azimuths in which it is placed. In proportion as the angle α increases, the cosine of that angle diminishes; and therefore the tangent of the angle ϕ, which expresses the angle the resultant makes with a vertical line, also diminishes. Hence, in proportion as the plane of motion comes nearer to a position perpendicular to the magnetic meridian, the position of the needle will approach more nearly to the vertical position; and it is exactly vertical when its plane of motion has arrived at that situation. This has been already noticed as affording a method of determining the position of the magnetic meridian, independently of the horizontal needle (§ 313).

(329.) We may deduce also the formula given in § 314, from the foregoing equations; for when the two azimuths in which the observations are made differ by 90 degrees, the tangents of ϕ in the two cases will be respectively

$\text{tang. } \varphi' = \text{tang. } d \cos. \alpha$

$\text{tang. } \varphi'' = \text{tang. } d \sin. \alpha.$

By taking the squares of each term of these equations, and adding them, we obtain

$$\text{tang.}^2 d = \text{tang.}^2 \varphi' + \text{tang.}^2 \varphi'';$$

which, when δ, δ' and δ'' express the angles of the dip, or the complements of d, φ, and φ'', respectively, become

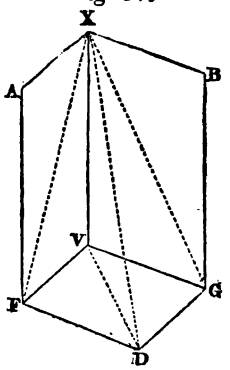
$$\cot.^2 \delta = \cot.^2 \delta' + \cot.^2 \delta''.$$

(330.) The same formula is derivable more simply from the following considerations:—

Let XD, *fig. 75*, be the line of dip in the magnetic meridian; and let XVFA, XVGB, be the two vertical planes at right angles to each other. From D, draw the lines DF and DG, perpendicular to these planes; and also FV and GV, perpendicular to XV. The lines XF and XG will be the positions of the needles in these planes, according

to the law already stated, § 78. Taking XV as radius, the lines VF, VG, and

Fig. 57.



VD are the tangents of the angles VXF, VXG, and VXD, respectively; and in the right-angled triangle VDF,

$$VD^2 = VF^2 + FD^2;$$

that is (FD being = VG)

$$VD^2 = VF^2 + VG^2:$$

or tang. ^2VXD = tang. ^2VXF + tang. ^2VXG; which is the formula above given.

(331.) On the other hand, the determinations of the relative intensities of the magnetic forces in different planes furnish data for the computation of the angles which those planes make with the line of the dip, or the direction of terrestrial magnetism. Thus the amount of the dip may be determined by comparing the number of oscillations in a given time made by the same needle, when vibrating in the plane of the magnetic meridian, and also in a vertical plane at right angles to it. For the squares of these numbers being as the intensities of the forces which respectively act in these planes, and the force in the former case being to that in the latter as the radius to the cosine of the angle *d*, which the line of dip makes with a vertical line, we obtain the latter by a simple proportion when the former are given. Resuming the notation before employed, let *e* be the total terrestrial force acting in the plane of the magnetic meridian, and *v* that part of it which acts in a vertical plane at right angles to the magnetic meridian; and let N and *n* express the number of oscillations, in a given time, which the dipping-needle performs in these two planes respectively: $v = e \cos. d$, or, *d* being the complement of δ;

$$v = e \sin. \delta;$$

$$\sin. \delta = \frac{v}{e}.$$

But $v : e :: n^2 : N^2$;

therefore $\frac{v}{e} = \frac{n^2}{N^2}$

and $\sin. \delta = \frac{n^2}{N^2}.$

(332.) We shall give the following example of the application of these formulæ to the observations of magnetic intensity, made by Humboldt, near Quito, exactly at the terrestrial Equator, and at longitude 81° 2′ west from Paris. The number of oscillations made by the dipping-needle vibrating in the magnetic meridian, during ten minutes, was 220; the number of oscillations, made in the same time, when it vibrated in a plane perpendicular to it, was 109. Substituting these numbers in the formula for N and *n* respectively, we obtain

$$\sin. \delta = \frac{109^2}{220^2} = \frac{11881}{48400}$$

From log.	11881	= 4.0748530
Subtract log.	48400	= 4.6848454
there remains log. sin. δ		= 9.3900076

whence we get $\delta = 14° 12′ 35″$.

The direct observation of the dip, by the dipping needle, was

$$\delta = 14° 25′ 5″,$$

the difference between the two methods being only 12′ 30″.

(333.) The angle of the dip with the horizon may, in like manner, be obtained by comparing the relative intensities of the forces, as determined by the squares of the number of oscillations in a given time, executed in the plane of the magnetic meridian, and also in a horizontal plane: for they are in the proportion of the radius to the cosine of the dip; or, if we call the number of oscillations made by the horizontal needle ν, while N is that made by the same needle, suspended as a dipping-needle, and placed in the plane of the magnetic meridian; then

$$\cos. \delta = \frac{\nu^2}{N^2}.$$

(334.) Methods have been devised for determining the dip, from the result of observations made with the horizontal needle alone, by comparing its number of oscillations with the weight of the counterpoise necessary for maintaining it in the horizontal position when magnetized. But the formula and mode

of computation are much more complicated than those we have given; and we must therefore refer our readers for the details to Biot's Traité de Physique *.

(335.) The determination of the intensity of terrestrial magnetism may, in general, be made with much greater accuracy, by observing the oscillations of a needle moving horizontally, than in any other way: because the mode of suspension we can employ for obtaining a horizontal motion is much more delicate, and much less impeded by friction, than any other motion on a fixed axis can be. The greater duration also of the period through which the oscillations continue enables us to ascertain with greater exactness the average time of the vibration. Hence a silken suspension is much to be preferred for delicate experiments with horizontal needles, to that of balancing them on a point by an agate cup.

(336.) The following description of the apparatus used by Captain Sabine, in the voyages to the arctic regions in the year 1822 and 1823, may furnish valuable practical information to those who may hereafter conduct experiments of the same nature †. A mahogany box was provided, made, for convenience, of an octagonal shape, with a top of stout glass; its height was fifteen inches, and its diameter sufficient to allow a horizontal bar of seven inches in length to vibrate freely when suspended by a silk line passing through a brass button, inserted in a perforation in the middle of the glass top. A metal circle, fixed in the bottom of the box, of rather more than seven inches diameter, measured the arc of vibration. The bar was carried in a light stirrup, into which it was slid until correctly balanced. The silk thread, from which the stirrup was suspended, was fifteen inches long, and consisted of a sufficient number of silk fibres to sustain the weight. In order to remove all influence from the tendency in the silk to untwist, a brass bar, equal in weight to the magnetic bar, was first introduced into the stirrup in place of the latter, and the silk thread allowed to untwist itself, and then adjusted by turning the button in such a manner as that the brass substitute should settle, when at rest, in the magnetic direction. This being now removed, the magnetic bar was replaced in the stirrup, and its horizontality ascertained by its accordance with the circle, the degree to which it settled being registered as the zero. It was then drawn about forty degrees out of the meridian, and retained by a copper wire passing through the glass top, and capable of being moved in azimuth from its outside, and of being raised so as to release the needle at pleasure, in order to commence its oscillations. These were not noticed until the arc had diminished to thirty degrees, when the registry of them commenced, and was repeated at the close of every tenth vibration, until the arc had still further diminished to ten degrees, when the experiment was concluded. The box was usually placed on the ground, in a sheltered situation, far from buildings, or other sources of local interference; the only adjustment required, besides that of the silk thread, was to render the graduated circle horizontal, which was accomplished by a pocket spirit level, and wooden wedges placed beneath the box.

(377.) Six bars were used in this apparatus, differing from each other considerably, both in rapidity of vibration, and in the duration of the interval of oscillation between thirty and ten degrees. They were seven inches long, a quarter of an inch broad, 0.15 inches thick, and strongly magnetized. When not in use, they were kept in pairs, in the usual manner, as described in § 218, *fig.* 60, being combined, with their opposite poles united, in separate boxes; and each bar was placed by itself in the direction of the meridian for two or three hours before its time of vibration was ascertained. The times were registered to fractional parts of a second by the beats of a chronometer, having a rate inappreciable in the interval.

(338.) It should be observed, however, that comparative experiments on magnetic intensities, made by the oscillations of needles balanced horizontally, are liable to a source of error when they are made in places in which the dip is considerably different. For one of the poles having a tendency to incline below the horizon, the axis of suspension must, in order to compensate for this tendency, pass through a point on that side of the centre of gravity, so as to give an equal preponderance to the other side. Hence arises a difference between the two arms of the lever, and consequently a difference

* Tom. iii. p. 33.

† Account of experiments to determine the figure of the earth, p. 477.

in the effect of the force applied to them. This circumstance has escaped the attention of the most skilful observers, although it is of sufficient importance to destroy all confidence in the comparison of experiments made in places where the dip is very different *.

(339.) We have seen the method by which the amount of the dip may be determined from the comparative intensities of magnetic force in the plane of the magnetic meridian, and in the horizontal plane. It is easy to see how, by reversing the process, we may arrive at the knowledge of the force of terrestrial magnetism in the magnetic meridian, from observations of the intensity in the horizontal plane, when the dip is previously known; for we have only to augment the former in the proportion of the cosine of the dip to the radius: or, what comes to the same thing, to multiply it by the secant of the dip. For since

$$\cos.\,\delta = \frac{v^2}{N^2} = \frac{h}{e};$$

it follows that

$$e = \frac{h}{\cos.\,\delta} = h.\ \text{sec.}\ \delta$$

(340.) The method of oscillations is not the only mode of determining the intensity of magnetic forces; for the same object may be attained by employing the balance of torsion: but in general the former method is, on many accounts, preferable.

(341.) It would conduce much to the future advancement of the science of Magnetism, if the absolute intensity of the terrestrial magnetic forces could be ascertained by a standard equally determinate as those by which we estimate the atmospheric pressure, or the temperature of different climates; for by repeating the same process of observation, in the course of successive centuries, we might learn whether the intensity of these forces experienced any variation similar to what we know takes place in their direction.

(342.) The method which first suggests itself, would be to observe the variation, the dip, and the intensity, by means of three needles, respectively appropriated to these objects, and carefully preserved, with a view to a repetition of the same experiments at distant periods of time. As it is possible that their magnetic power may become impaired by these long intervals of time, it would probably be necessary to magnetize them afresh, employing for that purpose the most efficacious methods, so as to induce a degree of magnetism which shall at first be considerably greater than what they are capable of retaining permanently. When left for a certain time to themselves, they will then return to their natural state of saturation, and in this state they may be subjected to the experiments in question. Our assurance of their attaining this determinate degree of magnetism may be increased by preserving a great number of needles, brought to this state, and noting their respective powers; which records may afterwards be compared with similar observations made at a future period; for if they should be found to have preserved among each other the same relative degree of strength, we may confidently conclude that no alteration has taken place in their magnetic constitution, and that they are well adapted to the determination of the absolute force of terrestrial magnetism.

(343.) If a method could be discovered of obtaining a material for the making of magnets of perfectly uniform composition and qualities, there would be no necessity to employ in this comparison the same identical magnets at the several times of observation. Steel would evidently be unfit for the purpose, its composition being necessarily variable. Nothing would answer so well as iron alone, which might be obtained in a state of perfect purity by proper chemical processes; for Coulomb found that pure iron, however soft, may be rendered nearly as retentive of magnetism as steel, by merely twisting it. All that would then be necessary, would be to regulate the degree of twist, so that it might be constantly the same for different pieces of iron: this might easily be accomplished, by taking them exactly of the same dimensions, and measuring the number of turns in the twist given to them. Each of the bars might then be magnetized to saturation, and employed either separately or in defined combinations, and their magnetic forces examined, both by the torsion balance, and by the method of oscillations*.

(344.) Poisson has also attempted to resolve this problem by considerations of a mathematical nature, for which we must refer to his memoir, read to the

* Pouillet, Elémens de Physique Expérimentale tom. i. p. 482.

* Biot, Traité de Physique, tom. iii., p. 144.

Academy of Sciences at Paris, in Nov. 1825, and of which an account is contained in Pouillet's Elémens de Physique *.

§ 7. *Experiments on the Magnetic Intensities at different Heights above the Surface of the Earth.*

(345.) In the year 1804, Messrs. Gay-Lussac and Biot undertook, at the desire of the French government, an aërostatic voyage, expressly for the purpose of ascertaining whether the magnetic force experiences any perceptible diminution at considerable elevations above the surface of the earth. De Saussure had inferred, from some experiments which he made on the Col du Géant, near Mont Blanc, the height of which is 3435 metres (about 11,270 feet), that the magnetic force of the earth was reduced to four-fifths of what it was in the plains below. The instrument with which he made these experiments was simply a magnetic needle, suspended by a very fine silk thread. Messrs. Gay-Lussac and Biot carried with them a needle, carefully constructed by Fortin, and magnetized by Coulomb, according to Æpinus's process. No iron was allowed to enter into the construction of the car of the balloon; the only articles of iron they carried with them, were a few knives and a pair of scissors, which were suspended in a basket below the car, at a distance of from twenty-five to thirty feet, so that they could have no sensible influence on the magnetic needle. The continual rotation of the balloon on its axis, during its ascent, seemed at first to present an insuperable obstacle to their observing the oscillations of the needle. But, by bringing themselves in a line with terrestrial objects and the sides of the clouds, they perceived that they did not always turn round in the same direction, the rotatory motion gradually decreasing, and then taking place in a contrary direction. By watching the short intervals during which they remained stationary between these opposite motions, they were enabled to observe five, or at most ten oscillations at a time; they were obliged, however, to be very careful not to agitate the car, for the slightest motion, such as that produced by letting the gas escape, or even that of the hand in writing, was sufficient to turn the balloon aside. With all these precautions, which required a great deal of time, they found means to make ten experiments in the course of the voyage, and at different altitudes. The conclusion they deduced from the average of all their observations is, that the magnetic force experiences no appreciable diminution at any distance from the surface of the earth, as far as 4000 metres, or 13,124 feet.

(346.) Many important facts relating to this question have lately been established by M. Kupffer, in the course of a journey to the neighbourhood of Mount Elbrouz, in the Caucasus, undertaken by order of the Emperor of Russia, in the year 1829, and of which an account has been given in a paper published in the Memoirs of the Imperial Academy of Sciences of St. Petersburgh*. M. Kupffer found that the intensity of terrestrial magnetism really decreased as he rose above the level of the sea; and that this decrease was much more considerable than is conformable with the commonly received hypothesis of a focus of magnetic forces situated at the centre of the globe. He even thinks that the experiments of Gay-Lussac and Biot, in the voyage just mentioned, should have led to the same conclusion, because, although they could not detect any difference in the apparent intensity, yet since the temperature of the elevated regions of the atmosphere in which they made their observations is exceedingly low, it is probable that the magnetic power of the needle itself was greater than in the warmer atmosphere at the surface of the earth; so that, unless the terrestrial force had really diminished, an increase of magnetic intensity would have been apparent, and would have been indicated by the increased frequency of the vibrations in a given time. As this increased frequency was not observed to take place, M. Kupffer concludes that the force of terrestrial magnetism is, in fact, less at the height to which they had reached, than it is at the surface of the earth. It is certain that, in all experiments of this kind, the temperature should be accurately noted, as constituting an essential element in the reasonings to be founded on them †.

Chapter VII.

Of the Magnetism of Bodies that are not ferruginous.

(347.) It has long been suspected that besides iron, other metallic substances

* Tom. i., p. 494.

* For 1830, p. 69.

† See Journal of the Royal Institution, vol. 1. p. 610.

are capable of exhibiting magnetic phenomena. Nickel, and also cobalt, have occasionally been found obedient to the action of the magnet; and sometimes to possess considerable degrees of polarity. Brass, which is a compound of copper and zinc, has likewise been observed to be magnetic under certain circumstances, especially after it has been hammered. Cavallo states* that, when quite soft, brass has generally no perceptible degree of magnetism; and even those pieces which have acquired this property by hammering, again lose it by annealing or softening in the fire. He seems to have ascertained that the magnetism acquired in the former state, is not owing to any particles of iron or steel imparted to the brass by the tools employed in the hammering; and that those pieces of brass which have that property retain it without any diminution after having been hardened and softened several times in succession. If one end only of a large piece of brass be hammered, that end alone is rendered magnetic. He found, however, that the magnetic power which brass acquires by hammering has a certain limit, beyond which it cannot be increased by further hammering; and that this limit is different in pieces of brass of different quality or thickness.

(348.) Cavallo next examined various pieces of copper by means of a delicately suspended needle; but never found them magnetical, except occasionally in those parts where a file had been applied, and where, consequently, some particles of steel, detached from the file, may have adhered to the copper. On hammering other pieces, both in the usual way, and also between flints, he failed in obtaining any decisive result. Zinc, whether hammered or not, showed no sign of magnetism whatever. Platina was found to possess a degree of magnetic power nearly equal to that of brass.

(349.) The magnetic power of brass is sometimes so considerable as to interfere very sensibly with the movements of the needle in compasses, in the construction of which brass is employed. A remarkable instance of this is given by Mr. Barlow†. Seebeck has recommended an alloy of two parts copper with one of nickel, as admirably adapted for the manufacture of compasses, from its being entirely void of magnetism*. We have seen, in the case of brass, that two ingredients, which in themselves, when separate, are devoid of magnetic susceptibility, acquire that property by combination. Mr. Hatchet ascertained that a large proportion of either carbon, sulphur, or phosphorus, combined with iron, enables it fully to receive and to retain the magnetic properties: but that there is a limit beyond which an excess of either of these substances renders the compound totally insusceptible of magnetism†. On the other hand, instances occur where the admixture of the minutest quantity of another body will entirely destroy the magnetic power of a metal possessing that power when in a pure state. Mr. Chenevix found that the addition of arsenic, in very small proportion, deprived a mass of nickel, which had previously manifested strong magnetic power, of the whole of its magnetism‡. Dr. Matthew Young states that the smallest admixture of antimony is sufficient to destroy the polarity of iron§.

(350.) In the mineral kingdom a great variety of substances, and even some of the precious stones, as the emerald, the ruby, and the garnet, exert a feeble yet sensible attraction on the magnetic needle; and sometimes even acquire a slight degree of polarity‖.

(351.) Later inquiries appear to have established the fact that all bodies whatsoever are, in a greater or less degree, susceptible of magnetism. We owe this discovery to Coulomb, who exhibited his experiments in proof of it at a sitting of the French Institute, in 1802. The bodies examined were cut into small cylinders, or bars, about a third of an inch in length, and about the thirtieth of an inch in thickness: but those which were metallic were formed into needles of about the hundredth of an inch in diameter. Each of these cylinders was suspended by a thread of raw silk, which, being exceedingly fine, could scarcely support more than from 100 to 150 grains without breaking: on this account it was necessary to reduce the needles to very small dimensions. They were placed, when thus suspended, between the opposite poles of two steel

* Philosophical Transactions for 1786, p. 62; and also in his Treatise on Magnetism.

† Essay on Magnetic Attractions, second edition, p. 17.

* Annales de Physique, 1826.

† Philosophical Transactions for 1804, p. 315. Nicholson's Journal, 8vo. vol. iii. p. 287.

§ Seebeck discovered that an alloy of one part iron with four parts of antimony exercised no power over the magnetic needle, even when in motion.

‖ Cavallo's Treatise on Magnetism, p. 73.

magnets, arranged in the same line, and separated about a quarter of an inch more than the length of the needle that was to oscillate between them. Whatsoever was the substance of which the needles were formed, they always ranged themselves accurately in the direction of the magnets; and if disturbed from this position, returned to it with oscillations, which were often as frequent as thirty or more in a minute, and considerably more frequent than when the magnets were removed: thus indicating a very decided force of attraction. Needles made of tin, lead, copper, silver, and gold, and cylinders of glass, chalk, bone, and different sorts of wood, together with a great variety of other organic substances, both animal and vegetable, were tried in succession, and with the same result.

These experiments were repeated in England, by Dr. Young, at the Royal Institution, but with less decided success: the force of attraction indicated was estimated at rather less than the two-thousandth part of the weight of the substance employed.

(352.) There are but two ways of explaining these phenomena: they are either owing to the presence of minute quantities of iron entering into the composition of all the bodies which manifest magnetic properties, or else they warrant the inference that all these bodies possess a certain degree of inherent magnetism. If the former mode of explanation be the true one, we shall be forced to admit that iron may exist in bodies, in quantities so minute as to elude detection by the severest chemical examination, and yet have sufficient power to be sensibly affected by a magnet. A set of very delicate experiments was undertaken by Coulomb with a view to determine this point: in the course of which he satisfied himself, that a smaller quantity of iron than can be discovered by any chemical test yet known, will, when added to a body, impart to it a very decided magnetic susceptibility. This is the case when a metal contains only the 130,000th part of its weight of iron. The magnetic powers of different specimens of metals were found to differ materially according to the methods employed for their purification. Hence he concluded that the greater part, if not the whole, of the effect observed, is to be ascribed to the presence of iron. So confident was he of the truth of this theory, that he imagined the magnetic action of all substances might safely be taken as a criterion of the proportion of iron they contain.

(353.) On the other hand, the indications of magnetic power given by nickel and by cobalt are far too considerable to be accounted for by the agency of any ferruginous admixture. Biot was in possession of a needle made of nickel, which Thenard had exerted all his chemical skill in rendering as pure as possible: the directive force of this needle, when magnetized, was not less than one-third of a similar needle made of steel*. Now the proportion of iron which, if added to the nickel, would be required to impart an equal degree of magnetic power, is far beyond what can ever reasonably be supposed to enter into the composition of nickel so purified. It is certainly just possible that nickel may be a compound metal, containing iron as one of its ingredients; but we are not justified in admitting an explanation so extremely hypothetical, especially as there are other facts besides those above mentioned, which tend strongly to corroborate the universality of magnetism. Of this nature are the evidences of an influence exerted by bodies not reputed magnetic, in controlling the oscillations of a magnetic needle placed in their immediate vicinity; and also the phenomena of the mutual influence exerted between these bodies and magnets, when the one is revolving rapidly, in exciting sympathetic rotation in the other. These very curious phenomena will be described in the ensuing chapter.

Chapter VIII.

On the Magnetism of Rotation.

(354.) Considerable light has lately been thrown upon the question of the universality of magnetism, by the discovery of the unexpected effects which result from the reciprocal action of magnets upon other bodies, when the one or the other is maintained in a state of rapid rotation. In the year 1824 M. Arago showed that if a plate of copper, or of any other substance, be placed immediately under a magnetic needle, it exerts sufficient influence upon its movements to diminish sensibly the extent of its oscillations, without, however, affecting their duration; and the needle is brought to rest in a shorter time than happened when no such substance is placed under it. The con-

* Traite de Physique, tom. iii., p. 126.

verse of this experiment was attended with still more striking effects. When a plate of copper, for example, is made to revolve with a certain velocity under a magnetic needle, supported on its centre, and contained in a vessel closed on all sides, the needle is found to deviate from its natural position in the magnetic meridian; and the deviation is greater in proportion as the rotation of the plate is more rapid. If the rapidity of revolution be sufficiently great, the needle will be brought to revolve also, and always in the same direction in which the plate is made to revolve *. The experiment was varied in the following manner:—A circular plate of copper, balanced on a point at its centre, was placed immediately under a strong magnet, to which a rapid rotatory motion was given; the copper-plate soon began to turn in the same direction, and acquired by degrees a very rapid velocity of revolution. It was found, also, that the oscillations of a copper-plate in a vertical plane, when suspended by an axis which passed at a small distance from its centre of gravity, were much impeded, and soon destroyed, when the plate was inserted between the two poles of a very powerful horse-shoe magnet. M. Arago was of opinion that these phenomena are inexplicable upon principles of ordinary magnetism, and considered them as the effects of some hitherto unknown power in nature. But subsequent inquiry seems to render it probable, that they are all reducible to the operation of known laws of magnetism.

(355.) Mr. Christie having observed a permanent change in the magnetism of an iron plate in consequence of a mere change of position on its axis, it occurred to Mr. Barlow that this change would be increased by rapid rotation. But on trial this was found not to be the case, the effect produced being merely temporary. The first experiments were made with a mortar-shell fixed to the mandril of a powerful turning lathe, worked by a steam-engine. When the ball was made to revolve at the rate of 640 times in a minute, the needle was deflected several degrees from its natural position, and there remained stationary during the motion of the ball; whenever the rotation ceased, the needle immediately returned to its original situation. On inverting the motion of the shell, an equal and contrary deflection took place. But although numerous trials were made under various circumstances, the law of the phenomena could not be deduced until the influence of the earth's action had been neutralized by means of other magnets perfectly adjusted. All the anomalies before met with now disappeared, and the following law was rendered manifest. When the needle and ball are both in the same horizontal plane, whatever may be the direction of the axis of rotation of the ball, if its motion at its upper part be made towards the needle, the north pole of the latter will be attracted; and if the contrary way, repelled. Hence he concluded, that when an iron body is put in rapid rotation on any line not coinciding with its magnetic axis, a temporary derangement takes place in its magnetic powers, equivalent in effect to the influence of a new axis of polarization, perpendicular to the planes passing through its axes of rotation and of ordinary polarization.

(356.) The next series of experiments on this subject are those of Mr. Christie*, who ascertained that a plate which, in a given position, produced a certain deviation of the compass, no longer produced the same deviation, after it had been carried round one entire revolution in its own plane, although brought to rest, and every part of the apparatus restored to its former place. This change in the directive power of the plate, produced by rotation, was greatest when its plane was parallel to the line of dip, and at the same time as little inclined to the horizon as this condition would allow; or, in other words, when the axis of rotation was in the plane of the magnetic equator, and also in a vertical plane, that is, in the magnetic meridian. Hence he deduced a law which may be thus expressed: — If we conceive a dipping-needle to lie in the centre of an imaginary sphere, having an equator situated in a plane intersecting perpendicularly the direction of the dipping-needle, and a circular plate of iron to be placed with its centre in the surface of that sphere, its plane being a tangent to that surface, when the plate revolves, the effect of its revolution upon the dipping-needle will be such that each side of the equator of the latter (that is, the portion of the equator which is situated in a line at right angles to the line joining the centres of the needle and plates)

* Bulletin Universel, vol. iii., p. 328; Annales de Chimie, xxviii., 325.

* Philosophical Transactions for 1825, p. 347.

will be deflected in a direction contrary to the direction in which that edge of the plate which is nearest to it moves. The deviations of the horizontal needle may be easily deduced from this law, by reference to the motions of this imaginary dipping-needle, for they will be such as tend to bring them into the same vertical plane with the latter, which is the situation in which it makes the nearest approach to its line of direction.

(357.) The investigation of this curious subject was further prosecuted by Mr. Babbage and Mr. Herschel, who, in conjunction, undertook to verify M. Arago's experiments*. After a few trials they succeeded in causing a compass to deviate from the magnetic meridian, and finally to revolve, by placing under it plates of copper, zinc, or lead, which were put into very rapid rotation. In order to obtain more visible and regular effects, however, they found it necessary to reverse the experiment, by setting in rotation a powerful horse-shoe magnet with its poles uppermost, the line joining them being horizontal, and its axis of symmetry being placed vertically; while a circular disc of the substance to be examined was suspended over this magnet. The disc was found to follow the motion of the magnet with various degrees of readiness, according to the substance of which it was made. They obtained in this way signs of magnetic susceptibility from copper, zinc, silver, tin, lead, antimony, mercury, gold, bismuth, and carbon, in that peculiar metalloid state in which it is precipitated from carbonated hydrogen in gas-works. Great care was taken, in the case of mercury, to secure the exclusion of iron. In other bodies which were tried, such as sulphuric acid, rosin, glass, and other non-conductors, or imperfect conductors, of electricity, no positive evidence of magnetism was obtained.

(358.) They next endeavoured to determine the comparative intensities of action of these different bodies. Two methods were used for this purpose; first, by observing the deviation of the compass over revolving plates of great size, cast to one pattern; and, secondly, by the times of rotation of a neutralized system of magnets suspended over them; and it is remarkable, that the places of zinc and copper in the scale, according as the one or the other of these two methods was employed, were the reverse of each other; although the same order was assigned to all the other bodies by both methods.

(359.) On trying the effect of the interposition of different bodies as screens, in cutting off or modifying the influence of the rotating bodies, they could not detect any interceptive power, except, as might be expected, in the case of an iron plate, which, when of sufficient thickness, completely destroyed all perceptible effect from rotation.

(360.) The magnetic energy developed by rotation was found to be much diminished by any interruption of continuity in the plate which was acted upon. This fact had previously been noticed by Arago; but the experiments of Mr. Babbage and Mr. Herschel have verified it in more detail, and have added the curious circumstance, that re-establishing the metallic contact with other metals, restores, in a great measure, the force which had been lost by the division of the substances; and this happens even when the metal used for soldering has, of itself, but a very feeble magnetic power; thus affording a means of magnifying weak degrees of magnetism. The reduction of the metals to filings, or to powder, was found to produce a still more remarkable diminution of their magnetic energy. The law of diminution of force by increase of distance was next investigated; but it appeared to follow no constant progression according to any fixed power of the distance, but to vary between the square and the cube.

(361.) The explanation of these curious phenomena has been attempted on the following principle—namely, that in the induction of magnetism, time enters as a necessary element; or, in other words, that a certain appreciable time is required both for the acquisition of magnetic polarity, communicated by induction from a magnetized body, and for its loss, when the body in which it has been induced returns to the neutral state by the subtraction of all extraneous influence.

(362.) In order to trace the operation of this principle, let us conceive the north pole of a magnet to move horizontally, at a little distance above a plate of metal, or other substance, having a very low degree of magnetic susceptibility, and also a very low degree of retentive power. The points over which it passes in suc-

* Philosophical Transactions for 1825, p. 467.

cession will not instantly receive all the magnetism which the magnet is capable of exciting in them; their state of maximum polarity, therefore, will not be attained until the magnet has passed for some small distance beyond them. Neither will they lose their polarity at the same instant that the magnet is still further removed. Thus, from both causes, there will always be, in the rear of the magnet, a space both more extensive and more strongly impregnated with the opposite polarity than in advance of it. Hence, there will arise an oblique action between the pole of the magnet and the opposite pole of the plate, thus lagging behind it, which will urge it to move in the direction of the magnet's motion. The development of the more distant polarity, similar in kind to that of the magnet, being more diffused, that pole will be both weaker and less oblique in its action, and will be much inferior in power to that of the nearer attracting pole. It is evident that the converse will also be true when the magnet is at rest, but free to move horizontally; and when the different parts of the plate are passed in succession under it, the latter will tend to drag the former after it with a velocity continually accelerating, till they move on together with the same velocities. It is also manifest, that the greater the relative velocity, the more will the pole, developed in the plate, lag behind the magnet, or the magnet (in the reverse case) lag behind the pole; the more oblique, therefore, will be the action, and the greater the velocity produced. The application of these principles to circular motion, or to the rotation of plates, is sufficiently obvious; but in this case, if the velocity be excessive, compared with the retentive power of the revolving substance, the latter may have completed a revolution before there has been time for its being affected to a degree sufficient to occasion motion in the magnet; the induced polarity will then be weakened, and its effects rendered insensible. This diminution of the total effect by a more general diffusion of polarity was imitated by sticking a great number of magnetized needles, vertically, through a light cork circle, having their north poles downwards, so as to form a coronet of magnets. This apparatus, suspended centrally over a revolving copper disc, was not sensibly affected; for the poles of all the magnets, acting in rapid succession upon all the points below them, produced nearly a uniform circle of southern polarity, whose equal and contrary actions on the needles would destroy one another.

(363.) Plausible as this theory may appear, it is yet embarrassed with many serious difficulties. It does not give any satisfactory explanation of the mode in which an attractive force, resulting from induction, between one pole of a magnet and the consequent polarity of the adjacent parts of a piece of copper—a force which is so feeble as not to produce any sensible effects when both these bodies are at rest—is immediately so greatly increased on their separation and continued removal from one another, so as to occasion a very considerable motion. The force producing that motion is, according to the theory, an attractive force; but Arago has shown that the general resultant of all the forces, which operate between the pole of the magnet and the plate, is a repulsive force, with relation to the line perpendicular to the surface of the plate. The following experiment proves this:—Suspend a long magnet by a thread, in a vertical position, to the beam of a balance, and counterpoise it by weights on the opposite side; if the plate be then revolved under the magnet, the equilibrium will cease, and the magnet will rise, or appear to become lighter, indicating its repulsion from the plate*

(364.) The latest experiments on this subject are those of Mr. W. S. Harris, of Plymouth, of which he communicated an account to the Royal Society, in June 1830†. Finding that the vibrations which attend bodies in rapid rotation are propagated to a remarkable extent along the solid parts of the apparatus by which a magnetic needle is suspended, and that they are also conveyed to great distances by the surrounding air, even when highly rarefied, he took great pains to obviate these two sources of fallacy. He accordingly conducted all his experiments in an exhausted receiver, the parts to be acted upon being effectually secured from the influence both of vibrations from solids and of aërial vortices. He conceives that, in general, sufficient care had not hitherto been taken to eliminate these several causes of error, and that we cannot repose that implicit confidence in the conclusions deduced from them which is required in

* Annales de Chimie, xxxii. 213.

† It has been since published in the Philosophical Transactions for 1831, p. 67.

a subject of so delicate a nature. He finds that the influence of a rotating body on the magnet is real, but more feeble than had previously been imagined; and that the law of intensity of action is directly as the rapidity of rotation, and inversely as the squares of the distances between the attracting bodies.

(365.) From some experiments which Mr. Harris lately exhibited at the Royal Institution of London, it appears, that a magnetic needle, partly neutralized with regard to the earth's action, and made to vibrate while surrounded by a massive ring of copper, or other substance of very weak magnetic energy, had its oscillations sensibly repressed by the presence of that substance, and that it arrived much sooner at a state of rest than when the ring was removed. The magnetic influence of rotating bodies was found to be intercepted by a variety of substances interposed between them.

(366.) His last communications to the Royal Society contain an account of experiments tending to show that every substance susceptible of magnetism by induction, when interposed as a screen, tends to arrest the action excited by a magnet on a third substance; and that this interceptive power is directly as the mass of the intervening substance, and inversely as its susceptibility to receive induced magnetism. A single plate of iron, for instance, about the sixteenth of an inch thick, is found effectually to intercept the action of a revolving magnet on a disc of copper; but the same result is not obtained when the disc acted upon, instead of being copper, is also of iron, unless the mass of interposed iron be very considerable. He afterwards determined that this interceptive influence depends, not merely upon the surface of the interposed iron, but is in proportion to its mass. Hence he was led to suspect that indications might be obtained of a similar influence, exerted by substances not of a ferruginous nature, if they were interposed in considerable masses; and this conjecture was verified on trying the experiment. He found that the action of a revolving magnet upon a disc of tinned iron was completely intercepted by masses of about four inches in thickness, of either copper, zinc, or silver, interposed between them.

(367.) It would appear, then, that this interceptive property is common to all matter, though possessed, in various degrees, by different kinds of substance; and that, in order to render it sensible, it is only requisite to employ them in masses proportionate to their respective magnetic susceptibilities. Lead, for example, which has a weaker magnetic susceptibility than copper, must be employed in a larger mass in order to produce an equal effect. By an extension of this principle, it would require a thickness of above thirty feet of ice, in order to render its interceptive power sensible.

(368.) It is not necessary, however, that the substance which exerts this controlling power over the action of a revolving magnet should be actually interposed between the magnet and the metallic disc. Mr. Harris found that, in the case of iron, a mass of that metal, when placed very near to that surface of the magnet most distant from the disc on which it was acting, had the effect of neutralizing its power. With regard to non-ferruginous bodies, it is very difficult to render this influence sensible, unless they are interposed in the direct line of action.

(369.) The temporary induction of magnetism may be conceived as taking place in two different ways: first, by the immediate action of the magnet upon each individual particle of the body on which magnetism is induced; or, secondly, by the action of each particle on the next adjoining to it in succession, constituting a continued and successive propagation of magnetism from the one to the other. Although both these kinds of induction may take place at the same time in the same substances, yet the degrees in which they are exerted seem to be in some inverse ratio the one to the other: for when the absorbing or retentive power of the substance is considerable, the power of the magnet is soon checked: because the particles of that substance first acted upon begin to operate as screens to the succeeding particles; and the induction, after a certain point, proceeds entirely by communication from particle to particle, until the whole has attained a state of permanence. When, on the contrary, the retentive power of the given substance is small, little or no interceptive influence can exist among its particles; and the induction will be produced solely by the direct action of the magnet on all the particles. Accordingly it is only by the succession or multiplication

of effect, resulting from the action of a great number of particles, that the controlling power of such a substance becomes sensible. To this cause is apparently owing the diminution of the action of a revolving magnet on a disc of copper, when the latter is intersected by radiating grooves: since a portion of the substance, every part of which is concerned in the full development of induced magnetism, is thereby removed. In confirmation of this reasoning, Mr. Harris found that the number of oscillations made in vacuo in a given arc, by a delicately suspended bar, surrounded by several concentric copper rings, did not materially differ from the number performed, in similar circumstances, by the same bar, surrounded by a solid mass of copper.

(370.) The effects of various metals in diminishing the oscillations of a magnetic needle, have been determined with considerable accuracy by Professor Seebeck. An account of his experiments is given in the Annales de Physique for 1826*.

(371.) With regard to the theory of magnetism, Poisson has remarked that there is no necessity for supposing that the phenomena of magnetism are produced in all bodies by a fluid, or fluids, possessing everywhere the same intensity of attractive or repulsive action, and therefore requiring to be considered as the same fluid in different substances. No doubt can exist as to the identity of the electric fluid; because we see it passing from one conducting body into another, and at the same time preserving all its properties, and exercising, in like circumstances, the same attractions and repulsions. But we have no evidence of this kind in the case of the magnetic fluids, because they are always confined to the same particles; and we cannot, by mere reasoning, decide whether the magnetism of two different bodies, such as pure iron and pure nickel, should be considered as the same imponderable substance. It would assist us in the determination of this question, were it ascertained that similar and equal needles of iron and of nickel, when submitted to the magnetic influence of the earth, or of any other magnet, would make an equal number of oscillations. An experiment was made by M. Gay-Lussac with this view, from which it would appear that the mutual action of the magnetic fluids contained in steel and in soft iron is decidedly greater than the mutual action of the fluids belonging to steel and to nickel. This experiment, however, is not decisive of the question, because we may still consider the magnetic elements of a body as not actually in contact, but as constituting assemblages of particles, in which the two fluids reside, and are separated by intervals not greater than the dimensions of those elements; and, as we formerly observed (§ 165), the ratio between the sum of the volumes of all these elements, and the total volume of the body, may be different in different substances, and at different temperatures, in the same substance. This diversity may explain the result of Gay-Lussac's experiment, without the necessity of the supposition of a difference in the intensity of the magnetic power in substances differently susceptible of magnetism*. But the interest which attached to speculations of this kind, are now, in some measure, superseded by the new theory of magnetism, proposed by Ampère: for an account of which, we must refer to the forthcoming Treatise on Electro-Magnetism.

* See Quarterly Journal of Science for January, 1828, p. 456.

* Mémoires de l'Académie Royale des Sciences, tom. v. pp. 252, 254.

ERRATA.

Page 64, *line* 35, *for* sin, *read* cos.
37, .. to the ..... to half the.
41, .. sin. ..... ½ sin.

ELECTRO-MAGNETISM.

Chapter I.

History of the Science prior to Oersted's discovery.

(1.) The analogies that exist between the phenomena of magnetism and those of electricity, in their general character, in the laws which govern them, and in the various combinations they present, are so extensive and so remarkable, as naturally to suggest the notion that the agencies themselves from which they proceed must be allied to one another by some close and intimate relation. Adventurous theorists have advanced the doctrine, that each of these principles is merely a modification of the other, and that both may be regarded as ultimately identical in their nature, constituting, instead of two separate and primary powers, a single power of a higher order of simplicity.

(2.) The connexion between magnetism and electricity was a favourite subject of speculation and inquiry among philosophers in the middle of the last century. Many were the efforts made to resolve this seductive problem, which continued, however, to baffle the labours of each succeeding experimentalist, who multiplied his attempts, and varied his processes, without approaching nearer to the point he aimed at; and also to elude the reasonings of those who theorized upon every new fact until they bewildered both themselves and their readers in the mazes of visionary and conflicting hypotheses.

(3.) In the year 1774, the following question was proposed by the Electoral Academy of Bavaria as the subject of a prize dissertation:—'Is there a real and physical analogy between electric and magnetic forces; and, if such analogy exist, in what manner do these forces act upon the animal body?' The essays received by the Academy on that occasion, were collected and published, ten years afterwards, by Professor Van Swinden, of Franeker, the author of one of the essays for which the prizes were awarded*. The conclusion to which he arrived, after a long and elaborate discussion of the subject, was, that the similarity between electricity and magnetism amounts merely to an apparent resemblance, and does not constitute a true physical analogy; whence he infers, that these two powers are essentially different and distinct from one another. The opposite opinion, on the other hand, was maintained by Professors Steiglehner and Hubner, who contended that so close an analogy as that exhibited by these two classes of phenomena, indicated the effects of a single agent, varied only in consequence of a diversity of circumstances. So many new facts have been brought to light since the time in which these authors wrote, that the reasonings adduced on either side in this controversy have now lost their interest, excepting that it is still curious to observe by what devious paths they were led away from the truth, at the moment when they had nearly reached it, and when a very slight variation in the form of their experiments would at once have disclosed it to their view.

(4.) Subsequent discoveries relating to the laws of electric and magnetic action, both as respects attraction and repulsion, and also induction, have tended to confirm the analogy between them, and to corroborate the opinion that they ultimately emanate from a common source. Electricity, it is true, affects every species of matter with which we are acquainted, in nearly an equal degree; while magnetism, although perhaps equally universal in its operation, yet acts very feebly, and probably unequally, upon most kinds of matter, and certainly exerts its principal energy upon iron, a circumstance which has, to

* His work is entitled 'Recueil de Mémoires sur l'Analogie de l'Electricité et du Magnétisme, couronnés et publiés, par l'Académie de Bavière, &c.' par J. H. Van Swinden. En trois tomes, 8vo. A la Haye. 1784.

this day, remained inexplicable, although we have acquired the knowledge that electricity, under certain modifications, will produce every effect of magnetism. Electricity, we know, may be transferred from one body to another, but magnetism can be excited by induction only, and is incapable of any similar kind of transference. Still, however, there existed many positive facts, which, independently of all analogy, demonstrated that the magnetic needle was occasionally influenced in its movements by the action of electricity; and that, in certain cases, the magnetic properties could be excited by electric explosions. The appearance of the aurora borealis, which has all the characters of an electric phenomenon, has been very frequently observed to be accompanied by a disturbance in the position of the compass; and a delicately suspended magnetic needle has generally exhibited, on these occasions, very frequent oscillations. Lightning, which is still more decidedly electric, has been known, in numberless instances, to destroy, and sometimes to reverse the polarity of the compass-needle; and many disastrous accidents happening to ships, in consequence of their mistaking their course, may very probably have been owing to this cause. In confirmation of this, we meet with a narrative recorded in one of the early volumes of the Philosophical Transactions *, in which the ship Alexander, being one hundred leagues from Cape Cod, in latitude 48°, encountered a violent thunder-storm; the mast was struck by lightning, which also reversed the poles of all the compasses in the ship, a change which was not discovered till the ensuing night, when the stars appeared, and it was found that they had been steering in the opposite course to that which they intended. It is also stated, that in one of the compasses, the end which had before pointed to the north now pointed to the west. Another instance is recorded in the same work †, where a stroke of lightning passed through a box containing a great number of knives and forks, melting some, and scattering the rest about the room. It was found that all those which were not melted had been rendered strongly magnetic, so as to take up large nails, and other pieces of iron, placed near them.

(5.) Experiments were tried with the electrical battery, in imitation of these effects, and in order to ascertain the circumstances on which they depended. But although steel bars were easily rendered magnetic by passing strong electric shocks through them, yet the results were by no means uniform, and no general law could be traced as governing the production and distribution of the polarity thus induced. A large proportion of the effects appeared to be referable to the concussion which the particles of the bar received in consequence of the violence with which the accumulated torrent of electricity rushed through them, thereby giving efficacy to the inductive influence of the earth. This influence, it is well known, depends altogether, as was explained in the Treatise on Magnetism (§ 109), on the position of the bar with relation to the direction of the dipping needle, which is the same as that of the action of terrestrial magnetism. The experiments of Mr. Scoresby *, made with a view of determining the amount of this influence when aided by electric concussion, fully confirmed the principle upon which that mode of explaining the phenomenon rests, by showing that the action of a powerful electric shock is, in a great measure, similar to that of a blow from a hammer, or to the forcible twisting of the iron, or any other kind of mechanical violence.

(6.) There still, however, remained many anomalous appearances, to the explanation of which this principle did not furnish the most slender clue. These anomalies presented themselves more especially when the electric discharge was made to pass transversely, or in oblique directions, through the bar; for it was found, in those cases, impossible to predict what direction the induced poles would assume, or even whether any distinct polarity would be communicated to the bar when so treated.

Nothing illustrates more forcibly the proneness of the human mind to draw general conclusions from insufficient data, than the various opinions so confidently maintained by different experimentalists on this subject. D'Alibard thought he had demonstrated, by his experiments, that the electric discharge imparts a northern polarity to that point of a steel bar at which it enters, and a southern polarity to that at which it

* Vol. xiv. p. 520. † Vol. xxxix. p. 74.

* Transactions of the Royal Society of Edinburgh, vol. ix.

makes its exit; and this quite independently of the position of the needle with respect to the magnetic poles of the earth. Wilke, on the contrary, imagined that he could establish the existence of an invariable connexion between the negative electricity and the northern polarity. The laborious series of experiments which were undertaken by Van Swinden, with the express view of reconciling these strange discrepancies, instead of settling the dispute, seemed only to leave it more than ever embarrassed with difficulties. About the year 1777, the celebrated Beccaria engaged in a similar investigation; and although he, like his predecessors, failed in discovering the true nature of the magnetic influence of electricity, yet he noticed a singular fact which occurred to him in the course of his experiments, but of which he does not appear to have appreciated the value. He found that a needle, through which he had sent an electric shock, had, in consequence, acquired a curious species of polarity; for, instead of turning as usual to the north and south, it assumed a position at right angles to this, its two ends pointing to the east and west. There is little doubt, that if he had followed up the inquiry which this important fact had opened to him, he would soon have arrived at the great discovery which was made about half a century afterwards by Oersted, and which has dispelled the whole mystery.

(7.) As nothing had been gained by following the more violent operations of highly condensed charges of electricity, other philosophers occupied themselves in the attentive study of the more tranquil influence of this agent, when merely accumulated in insulated conductors, and exerting simply its attractive and repulsive powers in conjunction with those of magnetism. But however these actions might be combined, nothing could be detected that indicated any interference of agency or modification of effect consequent on the combination. An electrified body is found to exert the same attractions and repulsions on a magnetized needle as it does on the same needle when devoid of magnetism; nor does it, like magnetism, exhibit any decided preference for iron, compared with its action on other metals. When the two agencies are united in the same body, as when bars of steel, already rendered magnetic, are also charged with electricity, and placed so as to act upon one another, their electrical and their magnetic actions appear to be perfectly distinct, and in no respect to influence or modify one another.

(8.) The discovery of galvanism, and the invention of the Voltaic apparatus, opened a new field of inquiry; for, by furnishing the experimentalist with the means of maintaining a continuous current of electricity in very large quantity, it enabled him to study the effects of this powerful agent under circumstances of a very different kind from those he had previously had under his command. The electro-chemical phenomena, brought to light by its application to another branch of physical science, for a long time occupied the talents and absorbed the attention of scientific men in every part of Europe; and many years elapsed before Voltaic electricity was applied with any success to determine the influence which it so directly exerts over magnetized bodies. The few inquirers who sought to establish a relation or identity between these two powers, excited but little attention, in consequence either of the obscurity of their reasonings or the inaccuracy of their experiments. The various hints interspersed among the journals of this period, respecting movements having been observed in the magnetic needle by the action of the Voltaic pile, were too vague and uncertain to warrant any determinate conclusion. The most definite and authentic narrative relating to this subject was that of Ritter, who asserted that a needle, composed of silver and zinc, had arranged itself in the magnetic meridian, and had been slightly attracted and repelled by the poles of a magnet. He also stated, that by placing a gold coin in the Voltaic circuit, he had succeeded in giving to it positive and negative electric poles; and that the polarity so communicated was retained by the gold after it had been in contact with other metals, and appeared, therefore, to partake of the nature of magnetism. A gold needle, placed in similar circumstances, acquired still more decided magnetic properties. These experiments suggested to Ritter some vague idea that electrical combinations, when not exhibiting their electric tension, were in a magnetic state; and that there existed a kind of electro-magnetic meridian depending on the electricity of the earth, at right angles to the magnetic poles. But these speculations were of too crude a nature to throw any distinct light on

the true connexion between magnetism and electricity.

Chapter II.

Account of Oersted's Experiments.

(9.) The real discoverer of the magnetic properties of electric currents was M. Oersted, Professor of Natural Philosophy, and Secretary to the Royal Society of Copenhagen. In a work which he published in German, about the year 1813, on the identity of chemical and electrical forces*, he had thrown out conjectures concerning the relations subsisting between the electric, galvanic, and magnetic fluids, which he conceived might differ from one another only in their respective degrees of tension. If galvanism, he argued, be merely a more latent form of electricity, so magnetism may possibly be nothing more than electricity in a still more latent form; and he therefore proposed it as a subject worthy of inquiry whether electricity, employed in this, its most latent form, might not be found to have a sensible effect upon a magnet. It is difficult clearly to understand what he means by the expression of *latent states*, as applied to electricity, but it may be sufficient for us to know that in the various endeavours he subsequently made to verify his conjectures, he was led to such forms of experiment as afforded decisive indications of the influence of Voltaic currents on the magnetized needle. Yet, even after he had succeeded thus far, it was a matter of extreme difficulty to determine the real direction of this action, and it was not till the close of the year 1819 that his perseverance was at length rewarded by complete success.

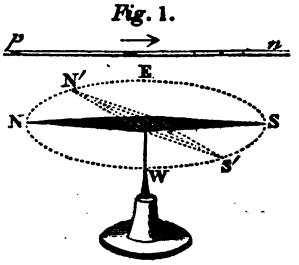
(10.) The first account of his discovery that appeared in England is contained in a paper, which he himself communicated, in Thomson's Annals of Philosophy, for October, 1820†; and in which the following experiments are described:—The two poles of a powerful Voltaic battery were connected by a metallic wire, so as to complete the galvanic circuit. The wire which performs this office he called the *uniting wire*; and the effect, whatever it may be, which takes place in this conductor, and in the space surrounding it, during the passage of the electricity, he designates by the term *electric conflict*, from an idea that there takes place some continued collision and neutralization of the two species of electric fluids, while circulating in opposite currents in the apparatus. Then taking a magnetic needle, properly balanced on its pivot, as in the mariner's compass, and allowing it to assume its natural position in the magnetic meridian, he placed a straight portion of the uniting wire horizontally above the needle, and in a direction parallel to it; and then completed the circuit, so that the electric current passed through the wire. The moment this was done, the needle changed its position, its ends deviating from the north and south towards the east or west, according to the direction in which the electric current flowed, so that by reversing the direction of the current the motion of the needle was also reversed. The general law he expressed as follows:—'That end of the needle which is situated next to the negative side of the battery, or towards which the current of positive electricity is flowing, immediately moves to the westward.'

(11.) The deviation of the needle is the same, whether the uniting wire, instead of being immediately above the needle, be placed somewhat to the east or west of it, provided it continue parallel to and also above it. This shows that the effect is not the result of a simple attractive or repulsive influence, for the same pole of the magnetic needle which approaches the uniting wire when placed on its east side recedes from it when placed on its west side.

(12.) If the uniting wire be placed in a horizontal plane *under* the magnetic needle the latter is affected to an equal degree as in the former case, but the motions are made in the contrary direction; for the pole of the needle next to the negative end of the battery now deviates towards the east.

(13.) The effects above described will

Fig. 1.

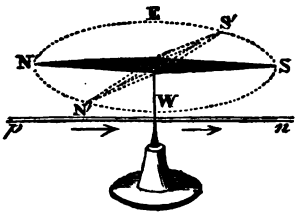


* This work was translated into French by Marcel des Serres, under the title of 'Recherches sur l'Identité des Forces Chimiques et Electriques. Paris, 1813.' See the 8th Chapter of that work.

† Vol. XVI. of the first series, p. 273.

be more clearly understood from an inspection of *Figs.* 1 and 2, where N, S present the two opposite poles of the magnetic needle, balanced upon its pivot; and *p n* the uniting wire; the end *p* being connected with the positive or copper end of the simple galvanic battery, and the other end, *n*, being connected with the negative or zinc end of the same battery. (See the Treatise on GALVANISM, § 15.) So that the direction of the positive electric current is from *p* to *n*, as described by the arrows in the figure.

Fig. 2.



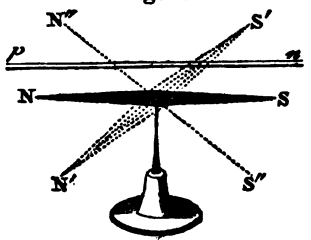
When the uniting wire is above the needle, as in *fig.* 1, the pole S, which is next to the negative side of the battery, or towards which the current of positive electricity is flowing, will move towards W, the western side of the horizontal dotted circle; and the needle will assume the position N′ S′. When the wire is below the needle, as in *fig.* 2, the same pole S will move towards E, the east point of the horizon; and its new position will be N′ S′, inclined in a direction the reverse of that which it assumed in the former case.

(14.) For the more easy retention of these facts in the memory Oersted used the following formula: namely, '*the* pole *above* which the *negative* electricity enters, is turned to the *west*; *under* which, to the *east*.' Another, and more convenient formula, however, will presently be given, comprehending not only these but many other facts, which are derived from a more universal principle applicable to all of them.

(15.) When the uniting wire is situated in the same horizontal plane as that in which the needle moves, and is at the same time parallel to it, no declination takes place either to the east or west; but the needle is inclined, so that the pole next to the end of the wire at which the negative electricity enters is depressed, when the wire is situated on the west side, and elevated when situated on the east side.

Thus, if the uniting wire *p n*, *fig.* 3, be placed on a level with the needle NS and parallel to it, on its eastern side, the pole S, next to the negative end of the wire *n*, will be elevated, and the pole

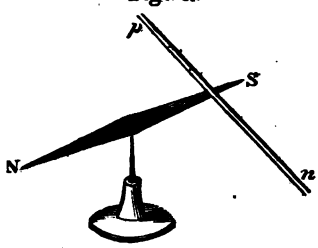
Fig. 3.



N depressed, so as to assume the position represented by the dotted needle N′S′. If the uniting wire had been placed on the western side of the needle the pole N would have been elevated, and S depressed; and the axis of the needle would have been in the position N″S″.

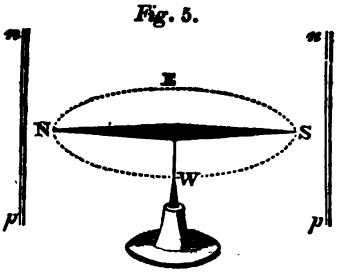
(16.) If the uniting wire, instead of being parallel to the needle, be placed at right angles to it, that is, extending from east to west, whether above or below it, the needle remains at rest, unless it be brought very near to one of the poles; in which case the pole is elevated when the entrance of the negative electricity

Fig. 4.



is from the west side of the wire, and depressed when from the east side. Thus the pole S, *fig.* 4, is elevated when the current of positive electricity proceeds from *p* to *n*; that is, when the entrance

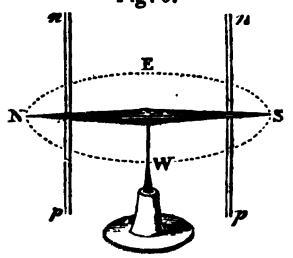
Fig. 5.



of the negative electricity is from the west side of the wire.

(17.) When the uniting wire, instead of being horizontal, is placed vertically, as shown in *fig.* 5, either to the north or south of the needle, and then brought near to the adjacent pole, if the upper extremity of the wire receives the negative electricity, that pole moves towards the east; but when the wire is brought opposite to a point between the pole and the middle of the needle, as in *fig.* 6, the

Fig. 6.



same pole deviates to the west. When the upper end of the wire receives positive electricity, the phenomena are reversed.

(18.) Oersted found that these experiments succeeded equally well if the uniting conductor consisted of one or of several wires, or metallic ribbons, connected together. Neither is the effect altered in its kind, though it may vary somewhat in degree, when different metals are used: thus, platinum, gold, silver, brass, iron, lead and tin, and even mercury contained in a tube, when employed as the conductors of the electricity, have a similar influence on the magnetic needle. The conductor still exerts this power, although it be interrupted by water, provided the interval between the metals does not extend to several inches in length. The magnetic influence of the wire on the needle is not prevented by the interposition of glass, metals, wood, water, resin, stones, or any other substance that was tried. The effect produced, nevertheless, is referable purely to magnetism, for it is exerted on magnetic bodies only, and has no influence on needles of brass, glass, or gum lac. It appears to depend, not upon the intensity of the circulating electricity, but solely on its quantity; and accordingly Oersted found that he could, with a single galvanic arc, repeat all the experiments which he had at first made with a compound Voltaic battery. In this way, also, he was enabled to detect the reciprocal action which the poles of a magnet exert on the conducting wire; for, by placing a plate of zinc, six inches square, between two plates of copper formed into a trough, in order to hold the acid which is to act upon the former, but kept from touching them by small pieces of cork interposed on each side, on forming a communication between the two plates by an extended wire, and then suspending the whole apparatus by a thread, the effect of a magnet in moving the wire could be readily ascertained.

(19.) The announcement of the important discovery of Oersted excited the greatest interest among all the philosophers of Europe, and they immediately occupied themselves in repeating and extending his experiments. Among those who were early distinguished by their zeal and activity in this research were Ampère and Arago, in France, and Sir H. Davy and Faraday, in England. So many were the cultivators in this new field of inquiry, and so eagerly did they pursue the path thus unexpectedly opened, that a great number of interesting facts were speedily brought to light; and where all were pressing forward in the same career, it is scarcely possible to adjust the claims to priority of discovery, with respect even to the most important facts. Instead, therefore, of attempting to give a chronological view of the progress of knowledge in this department of science, we shall adopt the following more didactic, and, we trust, more instructive plan. We shall first state those general principles to which philosophers have arrived by gradual and successive inductions; secondly, we shall trace the various combinations of those principles in different ways, and under different circumstances, and the effects resulting from them; and lastly, point out the explanations which they afford of particular phenomena, in the order which appears most conducive to clear and comprehensive views of the whole subject of electro-magnetism.

Chapter III.

Fundamental Law of Electro-Magnetic Action.

(20.) An attentive examination of the facts described in the preceding chapter will soon convince us that the magnetic force which emanates from the electrical conducting wire is entirely different in its mode of operation from all the other forces in nature with which

we are acquainted. It does not act in a direction parallel to that of the current which is passing along the wire, nor in any plane passing through that direction. It is evidently exerted in a plane perpendicular to the wire, but still it has no tendency to move the poles of the magnet, in a right or radial line, either directly towards or directly from the wire, as in every other case of attractive or repulsive agency. The peculiarity of its action is that it produces motion in a circular direction all round the wire; that is, in a direction at right angles to the radius, or in the direction of the tangent to a circle described round the wire in a plane perpendicular to it. Hence, as Mr. Barlow has expressed it, the electro-magnetic force exerts a *tangential action.*

(21.) The direction, in the circumference of these circles, of the action exerted on any one pole of a magnet by the electrical current which is moving at right angles to the plane of the circles, is determined by the direction of the current. If we suppose the conducting wire to be placed in a vertical situation, as shown in *fig.* 7, *p n*, and the current of positive electricity to be descending through it, or moving from *p* to *n* (the negative electricity moving, of course, in the contrary direction, or ascending), and if through any point C in that wire, the plane NN be taken perpendicular to *p n*, that is, in the present case, a horizontal plane; and lastly, if any number of circles be described in that plane having C for their common centre, then the action of the current in the wire upon the north pole of a magnet, situated any where in that plane, will be to move it in the line of the tangent to the circle which passes through it, and in the direction denoted by the arrows in the figure; that is, from left to right in the remote part of the circle, and from right to left in the nearer part. In other words, the motions impressed will be in a direction corresponding to those of

Fig. 7.

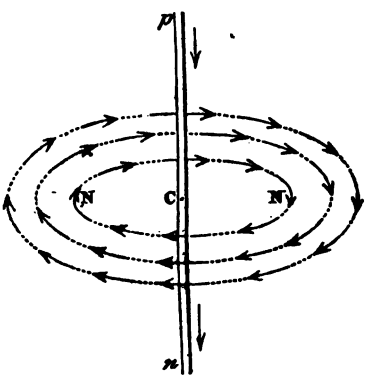
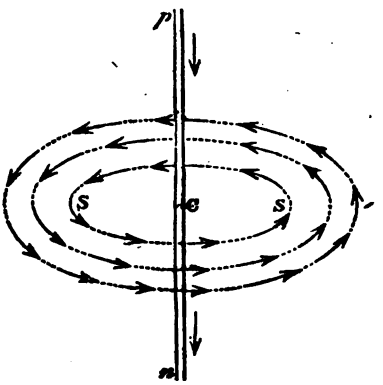


Fig. 8.



the hands of a watch having the dial towards the positive pole of the Voltaic battery.

(22.) When the direction of the current is reversed, the wire still preserving its vertical position, the direction of the action is also reversed; and the circular motions produced correspond to the movements of the hands of a watch with its face downwards; that is, still looking towards the positive electrical pole.

(23.) The actions of either the descending or ascending electrical current upon the south pole of a magnet are exactly the reverse of those which are exerted on the north pole. *Fig.* 8 represents the action of the current moving from *p* to *n*, on the south pole; which is directed, as may be seen, from right to left in that part of the circle which is opposite to the wire, and which would, therefore, impel the south pole in a direction contrary to that of the hands of a watch. On reversing the direction of the current these effects will again be reversed.

(24.) It is evident that in the course of experiments on electro-magnetism, the current and magnetic poles may be presented to our observation in a great variety of relative positions; and it will be found not very easy to retain a perfect recollection of the way in which the force should act conformably to the rule

above stated. Ampère has hit upon an ingenious device for imprinting this rule more firmly in the memory, and enabling us to apply it under a great diversity of circumstances. The electric currents are not only characterized as positive and negative, and as flowing in one or other of two directions along the wire that conducts them, but may be actually personified and conceived as endowed with a head and feet, with a face and back, and with a right and a left hand. In order to turn this idea to the best account, and being at liberty to choose, with respect to the various kinds of conditions belonging to the subject, one or other of two alternatives, we shall select in each case those which seem naturally entitled to the preference: and it fortunately happens that, on combining these conditions so selected, they accord exactly with nature, and are therefore well calculated to answer the purpose of a kind of artificial memory.

(25.) First, it is more natural to fix our attention on the current of *positive*, than of negative electricity. Secondly, in a vertical wire, a *descending* current will occur to us more readily than an ascending one: or, if we imagine ourselves borne along by the current, it would be more natural to conceive ourselves moving with our *feet* foremost; but if, on the contrary, we suppose ourselves to be at rest, we should conceive the current to be passing from our head to our feet. Our *face* would, of course, be turned *towards* the magnetic pole to which we are directing our attention; we should attend to the *north* pole in preference to the south; and the movement with which we are most familiar, is that which we perform with our *right* hand, as in writing for instance, that is, *from left to right*. Combining these conditions, then, we may always recollect, that *if we conceive ourselves lying in the direction of the current, the stream of positive electricity flowing through our head towards our feet, with the magnet before us, the north pole of that magnet will be directed towards our right hand.* If any one of these conditions be reversed, the result is reversed likewise.

(26.) The action of the conducting wire on the pole of a magnet is necessarily accompanied by a corresponding and opposite action of the magnet on the wire. When the wire impels the pole from left to right, the pole impels the wire from right to left, and *vice versâ*. Thus we have seen that a positive current, descending along a wire, of which W, *fig.* 9 A, represents the section by a horizontal plane, urges the north pole N to the right, in the direction N *n*, but the wire itself is also urged in the direction W *w*, to the left. The contrary action takes place between the south pole S, *fig.* 9 B, so that if either pole of a magnet were fixed, and the wire moveable, the motion of the latter would, as in the case we have already considered, be circular, and the force which impels it tangential. This is shown in *figs.* 10 and 11, where *pn*, *pn*, &c. show the successive positions of the wire urged to move in the direction shown by the arrows, by the influence

Fig. 9.

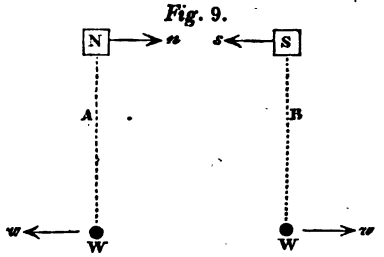


Fig. 10.

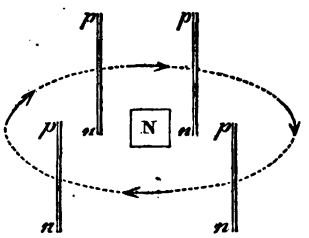
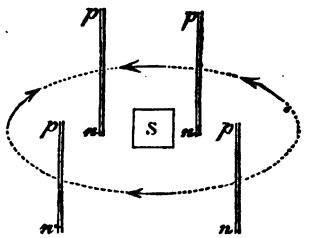


Fig. 11.



of the north or south poles N or S. The influence exerted on the same current by the one being in the opposite direction to that exerted by the other. When the currents are reversed, all the effects just described are again reversed.

It is also to be observed, that the motion of the wire, whatever be its relative position to the magnet, is always moved parallel to itself; that is, in the direction of a line at right angles to it.

(27.) The direction of the electro-magnetic force being thus determined, we have next to ascertain the exact law, according to which its intensity varies, with relation to the distance of the electric current from the point on which it acts. The most reasonable conjecture we can form on this subject, prior to experimental investigation, is, that this law is the same with that which is followed in the case of electric and magnetic actions, namely, that the intensity of the force is every where inversely as the square of the distance. But if this be the real law of action, it must apply to the elementary portions of the two agents which thus mutually act apon each other; or, to adopt the more convenient language of theory, it must obtain only among the elementary particles of the electric and magnetic fluids. In the magnet, the action of the latter may be regarded as concentrated in the points, which are the poles of the magnet; but in the conducting wire, the electric fluid which is passing through it, acts in an equal degree along the whole line of its motion; and admitting the hypothesis of the action being inversely proportional to the squares of the distances of each individual particle, we have to deduce the law which will result from the combined actions of all the points of a line directed upon a point out of that line. Now, it may be mathematically demonstrated, that if the line in question be perfectly straight, and its length be exceedingly great in proportion to the distance of the point on which it acts, then the intensity of action will be inversely proportional, not to the square, but to the simple distance of the point, so that at three times the distance, for example, the force shall be one-third, at four times the distance, one-fourth, and so on. That this law is conformable to observation, has been proved by the experiments conducted by Biot and Savart, in which the intensities of the force at different distances were accurately ascertained, by observing the number of oscillations performed by the needle in a given time, and taking the squares of those numbers.

Chapter IV.

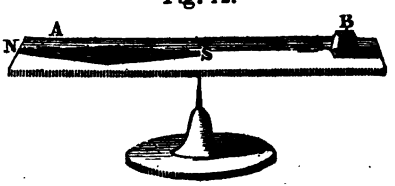
Direct consequences of the Law of Electro-magnetic Action.

(28.) Let us now inquire into the consequences of this law. So different is the action of the electro-magnetic force from that of the other forces in nature, with the effects of which we are more familiar, that a particular train of investigation is required, in order to trace its exact operation under every combination of circumstances. It is not easy, even in the simpler cases, where a single magnetic pole is subjected to the action of a conducting wire, at once to pronounce upon the precise motion that will result, especially if the motion of the magnetized body is limited to a fixed plane, and restrained to mere rotation; but the difficulty is much increased, when, as most frequently happens in actual experiment, the investigation is complicated by the necessity of including the combined actions of several poles of different kinds. The only mode of obtaining clear views of the subject is to examine the several cases in their order of simplicity, commencing with each force taken singly, and afterwards studying their several combinations.

§ 1. *Effects on the Directive Property of a Magnetic Needle.*

(29.) Confining our attention, then, for the present, to a single magnetic pole, the north pole for instance, we have to examine the effects produced upon it by a conducting wire of indefinite length, acting upon it with a tangential force inversely proportional to its distance, when the movements of that wire are limited to the circumference of a circle, in a given plane, perpendicular to the wire. The case under consideration may, in a great measure, be exemplified, by placing a magnet, SN, *fig.* 12, on a flat support, AB, resting, at its centre, on the pivot P, and balanced by a counterpoise at the opposite end, so that the south pole, S,

Fig. 12.

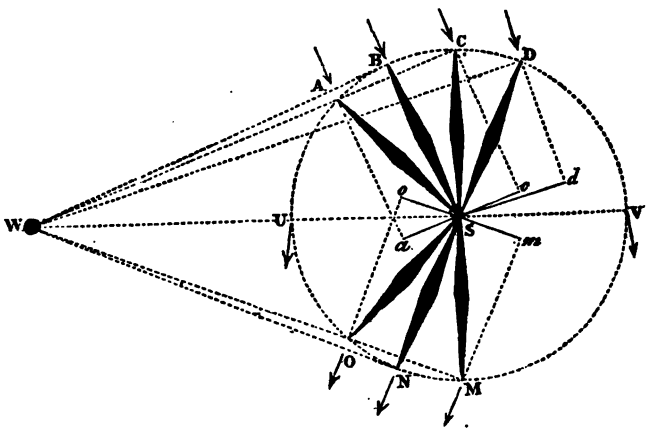


of the magnet may be exactly above the centre of motion.

In this situation, the action of any electrical current upon the pole S, can have no influence in turning the bar, AB, in any particular direction; and the motion of the bar will be determined solely by the action of the current upon the north pole, N.

(30.) Let A B C D M N O, *fig.* 13,

Fig. 13.



be the horizontal circle in which the needle NS revolves, S being the centre of its revolution; and let W be the horizontal section of the conducting wire, which acts upon the needle, and along which the positive electric current is descending. In every position of the needle, the tangential force, acting upon the pole in the circumference of the circle, takes the direction of a line to the right hand, perpendicular to that which connects the pole and the wire. At D, for instance, it has the direction of the line D *d*, perpendicular to DW. Its tendency to produce rotation in the needle, by turning it round S, will be proportional to the cosine of the angle formed between WD and the radius DS; or it may be represented by the line S *d*, drawn parallel to WD, and meeting the perpendicular D *d*, to which it is, of course, also perpendicular; for it will readily be seen, that the rotatory effect of the force we are considering is the same, whether applied on the needle at D, or at *d*, on the arm of a lever S *d*, rigidly connected with the needle. The needle, then, will be urged by this force to move towards V, and as the length of the lever by which it acts continually increases until it reaches this point, so also will the rotatory power increase. After the needle has passed V, it will again diminish; when it comes to M, its measure is S *m*, and on arriving at N, where the position of the needle NS is at right angles to NW, it is reduced to nothing. This, therefore, will be a position of equilibrium, and the equilibrium will be a stable one, for, on disturbing the position of the needle by pushing it onwards to O, for example, the rotatory force, in this new position, acts upon it by the lever S *o*, on the opposite side of S *m*, and, therefore, tends to give it rotation in the contrary direction; that is, to bring the pole of the needle back again to N. After performing a few oscillations, the needle will, therefore, finally settle in the position SN

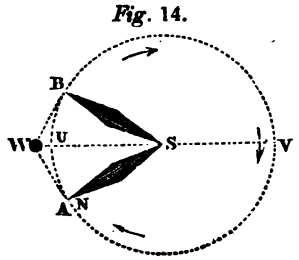
(31.) When the arcs of vibration are small, the forces which tend to bring the needle to its point of rest, are very nearly proportional to the arcs themselves; so that, in this respect, its movements are governed by the same law as those of a pendulum. They accordingly furnish very accurate means of determining the comparative intensities of the electro-magnetic forces which act upon the same needle under different circumstances of distance from the wire, or of intensity of the electric current, for the force will always be proportional to the square of the number of oscillations which the needle performs in a given time.—(See *Treatise on Magnetism*, § 320.)

(32.) When the needle is still further

deflected towards the wire, the force that tends to bring it back to the position of rest increases till it reaches its maximum at the position SU, where the needle points directly to the wire. Carrying it still further to the left, the rotatory force again diminishes, till it arrives at the position BS, perpendicular to BW, where, being directed to the exact centre of motion, it is reduced to nothing. This position of the needle, therefore, is also one of equilibrium; but it differs from the former in being an unstable equilibrium; for if the needle be disturbed ever so little from its position on either side, it will acquire a tendency to proceed onwards in that direction, and will move away from the point B. At A, for instance, the rotatory force acts upon it by the lever S *a*, urging it towards U, and causing it ultimately to settle at N. At C, again, it is urged towards D by a similar force, proportional to S *c*, and which, increasing as the needle advances, carries it to V, and finally brings it round to N.

(33.) It may here be remarked, that the rotations of the needle are in opposite directions in these two portions of the circumference; for, in the remote part, BVN, the motion is similar to that of the hands of a watch; in the nearer part, BUN, it is in the contrary direction. The lines WB and WN, drawn from W to the points where the needle is in equilibrium, being at right angles to the respective radii BS and NS, are tangents to the circle at B and N, and the circumference is divided by these points into two unequal portions, so that the needle, in passing from B to N, by the operation of the tangential force emanating from W, as indicated by the arrows in the figure, has to traverse a longer distance when moving in the remote than in the nearer part of the circle. The disproportion between these two arcs continually increases as the wire is brought nearer to the circle. When very near, as shown in *fig.* 14,

Fig. 14.

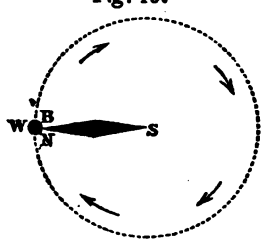


the arc BUN is very small, compared with BVN; yet, if the needle be placed ever so little on the other side of B, it will immediately recede from that point, as if repelled by the wire, and will proceed to describe the larger portion of the circle, in order to arrive at N, a position which it might have reached by a much more direct course had it described the arch BUN.

(34.) The singular preference thus shown by the needle for a very circuitous path, in reaching its destination, when it appeared free to take the shorter line that leads to it, appeared exceedingly paradoxical to those who first observed it, and excited much astonishment. But the explanation we have given shews clearly that it is nothing more than the direct result of the peculiar law of electro-magnetic force, which is characterized by the tangential direction of its agency.

(35.) If the wire be supposed to pass through the circumference itself, as in *fig.* 15, that portion of the circumfer-

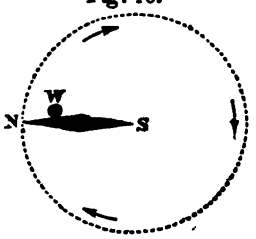
Fig. 15.



ence BN, which was comprehended between the two tangents, and in which the needle was urged to turn in a direction contrary to that of its revolution in the rest of the circle, is now reduced to a mere point; and the needle, when placed ever so little to the left of that point, will move round the entire circle, and even when it arrives at this point, can hardly be said to settle there, for the slightest movement in the same direction will again place it under the influence of the same impulse, which will, therefore, carry it round a second time. The very momentum it has acquired in this motion will be sufficient to transport it beyond this neutral point, and to maintain it in a state of perpetual revolution. Should the wire be actually within the circle, as in *fig.* 16, then the rotatory force will remain constantly in the same direction in every part of the circle, and, according to theory, the

needle will revolve in perpetuity in the same constant direction. It is obvious, however, that in the circumstances under which an experiment of this kind can be made, this can never happen, because the wire being a solid substance, and passing perpendicularly through the plane of the circle in which the needle turns, its presence must arrest the motion of the needle as soon as it comes in contact with it. The only position which the needle can take, therefore, is that of resting against the wire in the manner represented in *fig.* 16. In any

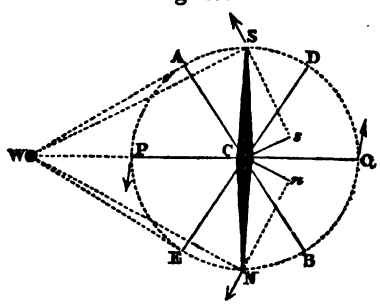
Fig. 16.



other part of the circle, it will move onwards in the direction indicated by the arrows.

(36.) Having thus investigated the action of an electric current on a single pole, we are now prepared for the consideration of its combined action upon the two opposite poles of a magnetized needle, balanced in the ordinary way on its centre. In this case, the current, descending through the wire W, *fig.* 17,

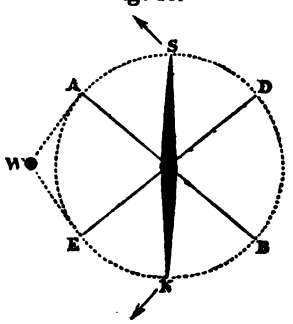
Fig. 17.



exerts a contrary action upon the two poles, N and S, of the needle. When the needle is in the position PQ, that is, in the same line with W, these two contrary forces, acting at right angles to the radius, and on opposite sides of the centre, concur in their rotatory effect, and the needle is urged by the sum of these forces to turn in the direction indicated by the arrows placed at these points. When the needle is in the position SN, at right angles to the line WC, the rotatory forces, being directed perpendicularly to WS and WN, as indicated by the arrows, oppose one another, and acting by the levers C*s* and C*n*, which are equal in length, are in exact equilibrium. The equilibrium is stable, as will be evident from considering that the displacement of S, in the direction of D, increases the length of the lever C*s*, while the accompanying motion of N towards E, diminishes the length of C*n*. The force represented by the former, will, therefore, preponderate over that represented by the latter, and will carry back the pole S to its former situation. The same would happen, were the displacement made on the other side of S, for in that case, the force which impels the pole N would have the advantage over that which acts on the pole S, and would restore the needle to its position of rest SN. This opposition of forces occurs when the needle is situated any where between the lines AB and DE, which are respectively perpendicular to the tangents to the circle, WA and WE; for, in either of these situations, AB or DE, the rotatory force exerted in one of the poles, is, as we have before seen, § 30, reduced to nothing. Beyond these positions, the rotatory force changes its direction, so that in any part of the arcs APE, and DQB, the forces acting upon the two poles conspire in producing a similar effect of rotation.

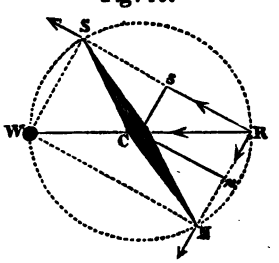
(37.) In proportion as the wire W, *fig.* 18, is brought nearer to the needle, the arcs ASD and ENB, in which the two forces oppose each other, form a larger portion of the circle, while those in which they concur, AE and DB, become smaller. Here it may also be

Fig. 18.



observed, that when the position of the needle differs much from that of SN, the two poles, N and S, will be at very different distances from the wire, and the intensity of the force being inversely as the distance, the forces acting upon the two poles will, in consequence, differ materially. When the forces concur in their rotatory effect, the result will not be affected by this difference; but when they oppose each other, the increase of force acting on the nearer pole, will go far towards compensating for the greater obliquity of its direction, and will bring it more nearly to an equality with the smaller force, which acts with greater mechanical advantage on the distant pole. This equality is actually attained when the wire passes through the circumference of the circle; for now the force acting upon S, *fig.* 19, in the direc

Fig. 19.

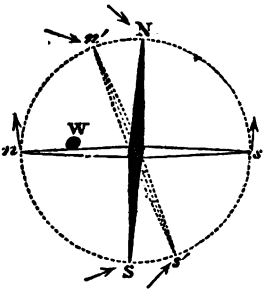


tion RS, is to the force acting upon N, in the direction RN, inversely as the distances WS and WN; that is, they are as WN to WS: but as the former acts by the lever C *s*, and the latter by the lever C *n*, which are themselves in the proportion of WS to WN, they must, by the laws of statics, be exactly in equilibrium.

To place the matter in another point of view, the forces RS and RN, when combined together, produce, as their resultant, the force RW, which, being directed to the centre of motion C, can have no tendency to produce rotation. Hence it follows, that the needle, whatever be its position in the circumference, will appear to be totally uninfluenced by the wire; the action of the latter, on both poles, exactly balancing each other.

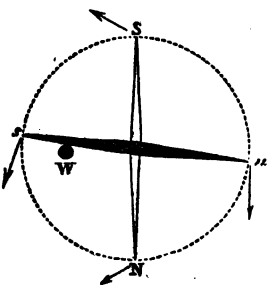
(38.) This state of equilibrium no longer remains when the wire is within the circle, *fig.* 20. It will now be found, that in no position of the needle do the two forces conspire to produce the same rotatory motion, and that they oppose one another in every part of the circle. The only position in which the equilibrium is stable, is that of NS, the north pole being to the left, and the south pole to the right of the wire; a position which, it should be observed, is exactly the re-

Fig. 20.



verse of that which the needle assumes when the wire is out of the circle, as in *figs.* 17 and 18. When disturbed from this position, and brought to *n' s'*, for example, the force urging the pole *n'*, which is nearest to the wire, becomes more effective than that acting upon the more distant pole *s'*, and, therefore, brings back the needle to its station. But if the pole N were placed on the opposite side of the wire, as at *n'*, the tangential force which carries it towards the wire, is, here also, more effective than that which acts upon the distant pole *s'*, and which tends to move it in the contrary direction; the needle, therefore, strikes against the wire, and being unable to pass it, remains in contact with it. If the needle be carried still further from the wire, however, the superiority of this force will continually diminish, and cease entirely when the needle is in the transverse position SN, shown in *fig.* 21, where the two poles, S and N, are equi-distant from W. Here there is again an equilibrium, but it is of

Fig. 21.

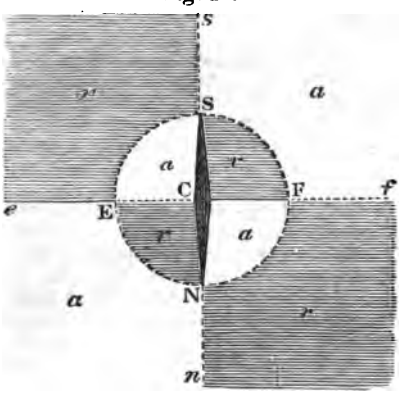


the unstable kind, for as soon as N is removed further from the wire, the force acting on S gains the advantage, and turns the needle round till its revolution is arrested by its coming against the wire, in the position *s n*.

(39.) Although, strictly speaking, the tangential force exerted by an electrical current upon either pole of a magnet, has no tendency to cause the pole to approach to, or recede from it, and, therefore, does not possess the character either of an attractive or of a repulsive force, yet the movements of a needle, in the circumstances we have just been considering, often resemble those of attraction and repulsion. But if viewed with reference to such a cause, they would appear exceedingly anomalous; and accordingly the sudden changes from attraction to repulsion, which take place from a slight alteration in the relative positions of the wire and needle, appeared to the earlier experimentalists to be very capricious and unaccountable.

(40.) In order fully to understand these transitions, we may arrange the results of the preceding investigation, as they refer to any one given position of the needle SN, *fig.* 22, varying the

Fig. 22.



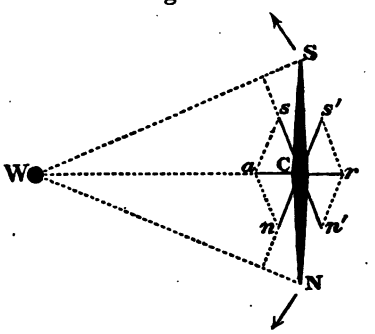
position of the wire only, and we shall then find that the lines which form the boundaries between the positions of apparent attraction and repulsion are the circumference of the circle of which the needle is a diameter, together with the prolonged axis of the needle *n s*, and another line crossing it, at the centre, at right angles, *e f*. The circumference indicates the positions of the wire when no apparent effect is produced on the needle, or the positions of neutrality. The line *e f* is that in which an equilibrium obtains. When the wire is in any continuous part of the line *e f*, namely CF and E *e*, the equilibrium is stable; when in any of the dotted parts E C or F *f*, of the same line, unstable; on the line *s n*, the action is at the maximum. The letters *a, a, a, a*, show the spaces where an apparent attraction takes place between the wire and the nearest pole, when the former is situated in the respective spaces bounded by the above lines; and *r, r, r, r*, the spaces where there is apparent repulsion. These latter spaces are shaded for the sake of distinction. Thus within the quadrant SCE there is apparent attraction of the pole S; in the shaded quadrant SCF there is an apparent repulsion of that pole; in the shaded quadrant ECN, the pole N moves from the wire; in NCF, towards it. In the spaces exterior to the circle the actions are exactly the reverse of those in the interior; in the shaded space bounded by *s* S, *e* E, and the circumference, the action in S is apparently repulsive; in the white space on the other side of S, bounded by the lines S *s*, F *f*, and the circumference, it is attractive; and the contrary obtains with regard to the spaces on the other side of the line *e f*.

§ 2. *Movements of the Magnetic Needle in free space.*

(41.) In the preceding investigation our attention has been exclusively directed to the determination of the effects of the electro-magnetic forces on a magnetized needle, so restricted in its motion as to be capable of only turning on its centre; and we have had to consider only the forces which tended to produce the rotation of the needle. A part of the forces, however, which act on the poles is exerted in another direction, and would, were the needle at liberty to obey them, occasion the displacement of the whole needle, that is, would produce a motion of its centre. The needle being confined by its pivot, the only effect produced by these forces is pressure upon this pivot. But if this obstacle be removed, and the needle be allowed to move freely in any direction, the action of these remaining forces will become manifest; the motion of the centre of the needle being determined in its quantity and direction by the magnitude and direction of the resultant force estimated by referring the two component forces to that point.

(42.) When the conducting wire W, *fig.* 23, is situated in any part of the line

Fig. 23.



WC, at right angles to the axis of the needle, the tangential force acting on the pole S, in the direction represented by the arrow, at right angles to WS, may be supposed to be transferred to the centre, C, of the needle, and to be represented by the line C s. The force acting upon N being in like manner represented by C n; the resultant of these two forces will be a force represented by the diagonal C a of the parallelogram, having C s and C n for its two sides, and these sides being equal, and equally inclined to the line WC, this diagonal will coincide with that line: hence the force will be such as to move the centre of the needle directly towards W, that is, the needle will appear to be attracted by it. If either the current had followed an opposite course, or the poles of the needle had been reversed, the forces would have acted in the opposite direction, and would have been represented by the lines C s', C n', forming a parallelogram, of which the diagonal is C r, indicating a motion of the centre of the needle from the wire, and resembling repulsion. This effect also takes place under the original circumstances of the experiment when the wire is on the other side of the needle, that is, in any part of the line CW; so that the needle will always appear to be attracted by the wire on one side and repelled on the other.

(43.) The intensity of the force which thus impels the needle, either towards or from the wire, diminishes as their distance is increased. Two causes conspire to produce this diminution; the one is that the component forces themselves are inversely proportional to the distances of the points on which they act from the wire; and the other is that the angles they form with one another become more obtuse as that distance increases. Mathematically speaking, the tangential force applied to each pole, when referred to the direction of the line joining the wire and the centre of the needle, is directly as the cosine of the angle formed between the axis of the needle and the line connecting the pole and the wire; and it is also inversely as this line; so that calling the force referred to that direction a, the distance from the wire to the centre of the needle d, the distances of the wire from the respective poles S and N, s and n, and the length of the needle m; and α and β being the angles between the axis of the needle and the lines connecting the respective poles with the wire, we have the following equation:

$$a = \frac{\cos.\ \alpha}{s} + \frac{\cos.\ \beta}{n}.$$

But as we have taken the case of W being placed on the line drawn from the centre of the needle at right angles to its axis, the two angles above mentioned are equal, and every part of the line is equidistant from S and N, that is,

$$\alpha = \beta, \text{ and } s = n;$$

hence the equation becomes $a = \frac{2 \cos.\ \alpha}{s}$.

Now

$$\cos.\ \alpha = \frac{CS}{WS} = \frac{\frac{1}{2} m}{s};$$

which value of cos. α being substituted in the former equation, the formula becomes

$$a = \frac{m}{s^2},$$

that is, the force of apparent attraction is directly as the length of the needle, and inversely as the square of the distance of the wire from each pole.

(44.) In order to estimate the attraction with relation to the distance of the wire from the centre of the needle, or d, we must substitute for s^2 its equal $d^2 + \frac{1}{4} m^2$; so that the formula becomes

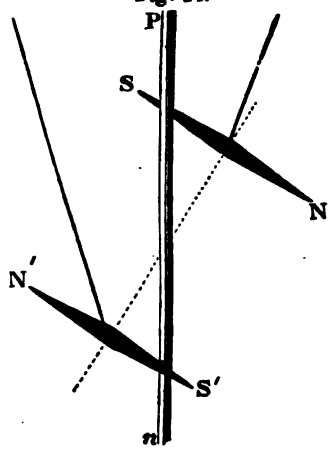
$$a = \frac{m}{d^2 + \frac{1}{4} m^2}.$$

But when the distance of the wire is very great compared with the length of the needle, the quantity $\frac{1}{4} m^2$ may safely be neglected; and $\frac{m}{d^2}$ may be taken without any sensible error as the expression of the attractive force.

(45.) This may be experimentally illustrated by suspending a magnetic needle, SN, *fig.* 24, from its centre by a thread,

so that it may be balanced horizontally, and bringing it within a certain distance of a vertical conducting wire P n; if the electrical current be descending in that

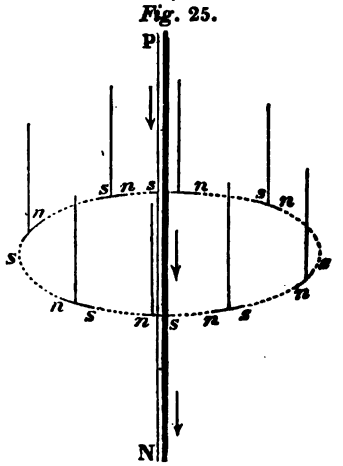
Fig. 24.



wire the needle will place itself so that the north pole N will be to the right, and the south pole to the left of a spectator conceived to be placed in the situation of the wire and looking towards the needle, as shown in the figure; whereas if the needle be before the wire as at N′S′ the poles will have a reverse position. In both cases the needle will be impelled towards the wire, as shown by the inclination of the thread by which it is suspended.

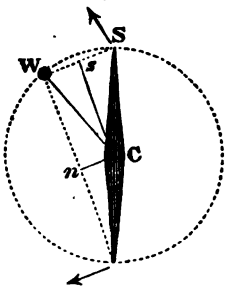
(46.) When, on the other hand, the needle is removed to a considerable distance from the wire, or what comes to the same thing, when a very short needle, s n, is taken and carried round the wire P N, *fig.* 25, in a circle, its poles will always preserve the same relative situation, as indicated by the letters in the figure, each being turned in the direction in which they are respectively urged to move round the circumference by the tangential force. But the tendency to approach the wire will be quite insensible, in consequence of the angle formed by the directions of the two forces being so nearly equal to two right angles.

Fig. 25.



(47.) When the wire is placed in any part of the circumference of the circle, having for its centre the centre of the needle, and passing through the poles, the resultant of the two forces C s and C n (*fig.* 26), has the exact direction of the line CW; and therefore, neither

Fig. 26.

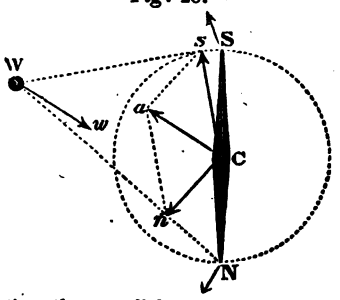


in this, nor in the preceding case, is there any rotatory force in operation. But, in the present case, the force CW being oblique to the axis of the needle SN, a part of that force is exerted in moving the needle in the direction of its length, from C towards S, and in bringing the centre C opposite to W; so that it will not rest until that centre comes in contact with the wire, as shown in *fig.* 27. A similar tendency in the centre of the needle to move towards the wire takes place in all other situation

Fig. 27.

of the wire on that side of the needle; but the direction of the motion produced is more or less oblique to the line connecting the centre of the needle with the wire. This direction may, in all cases, be easily found by drawing the lines C *s* and C *n* (*fig.* 28), respectively perpendicular to WS and WN, and com-

Fig. 28.

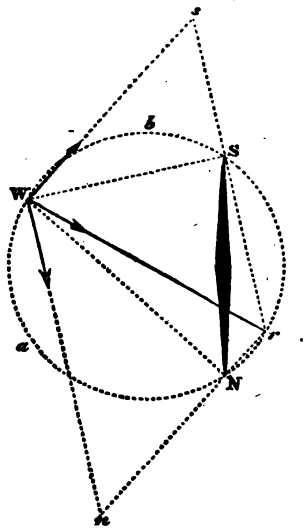


pleting the parallelogram C *s a n*; of which the diagonal, C *a*, will be the direction of the resultant force acting upon C. For the forces at S and N, being inversely as the distances WS and WN, are in the ratio of WN to WS, which is equal to the ratio of the sines of the opposite angles WSC to WNC of the triangle WSN; that is, in the ratio of C *s* to C *n*, which are the actual sines of those angles with the equal radii SC and NC. The lines C *s* and C *n* will, therefore, correctly represent, both in their directions and in their relative proportions, the tangential forces in question.

(48.) The actions exerted between the wire and the poles of the needle, are, as we have seen, reciprocal; the wire being urged by a force equal in intensity, and parallel in its direction, to that which acts upon the centre of the needle; hence the determination of this resultant force will also give us the measure and direction of the resultant of the two forces which act upon the wire. Thus the needle SN, *fig.* 28, being urged by a force represented by C *a*, the wire W will, in like manner, be impelled by a force represented by the line W *w*, equal and parallel to C *a*, but having an opposite direction.

(49.) The direction of the force impelling the wire by the joint action of the poles of the needle, may be found geometrically, by describing a circle W *b* S *r* N *a*, *fig.* 29, which shall pass through the position of the wire, and also through the two poles; for the diameter W *r* of that circle will be the direction required. This will appear from the following demonstration:—

Fig. 29.



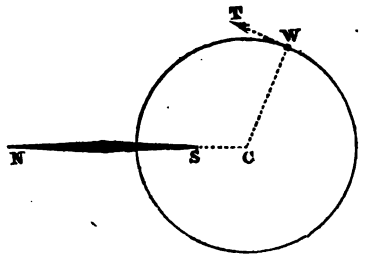
Through S and N draw S *r* and N *r*, respectively perpendicular to WS and WN, and which will, of course, meet at *r*, the extremity of the diameter W *r*; and through W, draw W *s* and W *n*, parallel respectively to *r* N and *r* S. meeting them, when produced, in *s* and *n*, and forming a parallelogram, of which W *r* is the diagonal. The triangle W *r s*, or its equal, W *r n*, is similar to the triangle WSN, because the angles WNS and W *r* S, which subtend the same arc W *b* S, are equal; as also the angles WSN and *s* W *r*, or its equal W *r* N, which subtends the same arc W *a* N. The sides of these triangles are, therefore, proportional; that is,

WN : WS :: *s r*, or its equal W *n* : W *s*.

But the tangential forces impelling W in the directions W *n* and W *s*, from the actions of the poles S and N, are inversely as the lines WS and WN; that is, directly as WN to WS, and therefore in the ratio of the line W *n* to the line W *s*. These lines will, therefore, represent, in their magnitudes as well as in their directions, the two tangential forces by which W is impelled; and consequently the diagonal W *r* of the parallelogram of which they are the sides, or the diameter of the circle, will represent the direction of the resultant force in question.

(50.) Hence it follows that the wire is, in all situations, impelled to move in the direction of the tangent of a circle having its centre in the prolongation of the axis of the magnet, and of which the radius is a mean proportional between the distances of its centre from the two poles. Thus the wire at W, *fig.* 30, is impelled by the

Fig. 30.



action of the two poles N and S, in the direction of the tangent of the circle of which the centre is at C, in the line NS prolonged, and of which the radius WC is a mean proportional between CS and CN. It will, therefore, revolve in that circle, which will stand in the same relation to the magnetic poles N and S, with regard to the law of electro-magnetic action, that the magnetic curves (See *Magnetism*, § 81) do with regard to the law of magnetic action.

Chapter V.

Application of the principles to the explanation of particular facts.

(51.) The principles we have derived from the preceding investigation are the foundations of the whole science of electro-magnetism, and furnish the key to the explanation of a vast variety of facts, some of which might appear, without an accurate attention to the circumstances of the case, exceedingly anomalous and perplexing. It is evident that they completely accord with the results obtained in the original experiments of Professor Oersted, which could not for some time be clearly understood.

(52.) In these experiments it will be recollected the wire was horizontal, and applied either above or below the needle, and in a direction parallel to it. In this case the action of the wire is exerted in the tangent to the circumference of a vertical circle, having the wire for its centre; and this action being in opposite directions upon the two poles, conspire to give the needle a motion round its axis. But the needle, having already a tendency to place itself in the plane of the magnetic meridian, in consequence of the influence of the earth, will arrange itself in a position intermediate between this plane and the position to which it tends by the action of the electric current. The greater the intensity of the latter force, the greater will be the deviation of the needle from the magnetic meridian; and both the amount and the direction of the deviation will be found on an attentive examination of the results of Oersted's experiments, as already detailed, to be exactly conformable to theory.

(53.) When the wire, still kept in a horizontal position, was placed by Oersted at right angles to the needle, and over its centre, no visible effect took place, because the actions of the wire upon the two poles were then exactly balanced. But whenever it was brought nearer to one of the poles than to the other, the vertical action being more strongly exerted upon that pole, occasioned its elevation or depression, according to the direction of that action, precisely in the manner which the theory would lead us to expect.

(54.) Mr. Barlow undertook a series of experiments to determine the deviations of a magnetic needle from its natural position, produced by a vertical conducting wire under different circumstances, and deduced from the theory various formulæ, by which its amount may be calculated. For the details of his researches, the reader is referred to Mr. Barlow's Essay on Magnetic Attractions *.

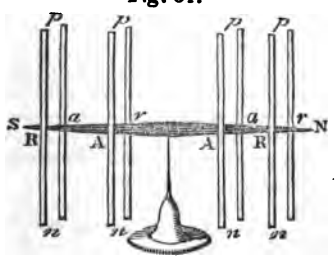
(55.) Of the speculations and hypotheses to which these extraordinary facts gave rise we shall defer the consideration to a future place, and, confining our attention to the facts themselves, we should here notice the observations of Mr. Faraday, which led to the more striking illustrations of the theory of tangential action we are about to describe. Mr. Faraday states † that on placing the wire perpendicularly, and bringing the needle towards it, in order to ascertain its positions of attraction and repulsion with regard to the wire, instead of finding these to be four, one attractive and one repulsive for each pole, he found them to be eight; that is two attractive and two repulsive for each pole. Thus, allowing the needle to take

* Second edition, p. 240.
† Quarterly Journal of Science, vol. xii. p. 75.

its position of equilibrium across the wire, and then drawing away slowly the support of the needle from the wire, so as to bring the north pole, for instance, nearer to it, there was attraction; but on moving it a little farther, so that the end of the needle was the point nearest to the wire, repulsion took place, although the wire was still on the same side of the needle. When the wire was on the other side of the same pole of the needle, it repelled it when opposite to most parts between the centre and the end; but there was a small portion, at the very end, where attraction took place.

(56.) *Fig.* 31 exhibits a compendious view of the relative situations of the needle and wire in these experiments;

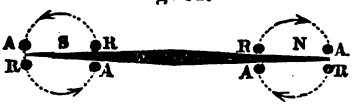
Fig. 31.



the electric current being supposed to descend along the vertical wire, *p n*, represented in eight different positions; the letters A, *a*, R, *r*, denoting respectively the apparent action (whether attractive or repulsive) exerted in each of these positions. A reference to *fig.* 22, and the general results stated in § 40, will sufficiently explain the facts mentioned by Mr. Faraday, if we take into account a circumstance which very generally obtains in needles of the pointed shape of those employed in the experiment; namely, that the centre of the active portion of each half of the needle, or its true pole, is not situated at the very extremity, but at some point near it, and towards the centre of the needle. Thus the wires in the extreme positions at the ends of the needle were in fact placed beyond the poles, and corresponded in their situation to points out of the circle passing through those poles, which is the circle given in *fig.* 22.

(57.) The reaction of the needle on the wire in these situations was also pointed out by Mr. Faraday, and illustrated by reference to the following figure (32), which represents horizontal sections of the wire in different positions with regard to the needle, balanced in its centre C. They are marked A or R,

Fig. 32.



according as they appear to attract or repel the adjacent poles S and N; and the arrow-heads indicate the directions of the circular motion which resulted.

(58.) Mr. Faraday justly concluded from these facts, that there is no real attraction or repulsion between the wire and either pole of a magnet, the actions which imitate these effects being of a compound nature; and he also inferred that the wire ought to revolve round a magnetic pole, and a magnetic pole round a wire, if proper means could be devised for giving effect to these tendencies, and for isolating the operation of a single pole. For the first idea of the possibility of the rotations of an electro-magnetic wire round its axis by the approach of a magnet, we are indebted to the sagacity of Dr. Wollaston *, who did not, however, succeed in producing this effect in the experiments which he made for that purpose.

Chapter VI.

Electro-magnetic Rotations.

(59.) The continued revolution of one of the poles of a magnet round a vertical conducting wire was produced by Mr. Faraday in the following manner †: —That the action of the wire might be limited to the pole in question, the whole magnet, with the exception of that extremity in which the pole was situated, was immersed in mercury, its lower end being attached by a thread to the bottom of the vessel which contained the mercury, the conducting wire being made to pass down into the mercury, immediately above the place where the copper wire was fixed to the vessel. This apparatus is represented in *fig.* 33, and a section of it shown in *fig.* 34.

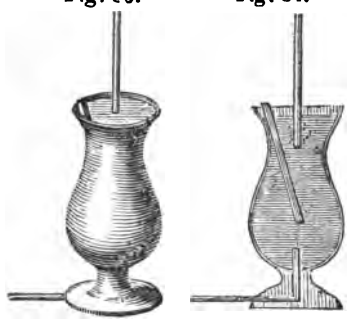
For the purpose of directing the electrical current through the mercury, hole was drilled at the bottom of the cup, into which a copper pin was ground tight, projecting upwards a little way into the cup, and rivetted to a small

* Philosophical Transactions for 1823, p. 158.
† Quarterly Journal of Science, xii. p. 283.

+ For afs. & illustrations see Amer. Journal of Science for May 1829

round plate of copper, forming part of the foot of the vessel. A similar plate of copper was fixed to the turned wooden base on which the cup was placed, and

Fig. 33. *Fig.* 34.



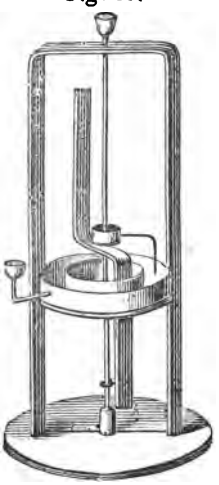
another piece of strong copper wire, attached to it beneath, after proceeding downwards a little way, was made to turn horizontally. The surfaces of these two plates, intended to come together, were tinned and amalgamated, that they might remain longer clean and bright, and afford better contact. The magnet used was of a cylindrical shape, and very powerful, and had its lower pole fastened by a piece of thread to the copper pin at the bottom of the cup. The height of the magnet and length of the thread were so adjusted, that when the cup was nearly filled with clean mercury, the free pole floated almost upright on its surface. The upright wire, communicating with one of the poles of the voltaic battery, and conducting the electrical current intended to act on the upper pole of the magnet, passed downwards from the upper branch of a stand, so as to descend to a small depth below the surface of the mercury. Its lower end was amalgamated, in order to ensure perfect contact; the circuit was completed by making a communication between the lower wire and the other pole of the battery. As soon as the current is thus established through the apparatus, the upper pole of the magnet immediately revolves round the wire which dips into the mercury. As the force which impels it continues to act without diminution, notwithstanding the motion of the magnet, it operates as an accelerating force; but the motion of the magnet in a circle giving rise to a centrifugal force, the magnet is carried to a greater distance from the wire, until its increased momentum is compensated by the increased resistance of the mercury, at which period the velocity becomes uniform.

(60.) The direction of the motion depends on the direction of the current, and on the denomination of the pole that is moved by it. If the current descends, the north pole of a magnet revolves from left to right; that is, in the direction of the hands of a watch. If the revolving pole be the south pole, it moves in the contrary direction. All this is in perfect conformity with what has already been explained in § 21, 22, and 23, and illustrated by *figs.* 7 and 8.

(61.) With a view of diminishing the resistance to the revolution of the magnet, which must necessarily take place when it has to revolve in mercury, attempts have been made to devise a method of suspending the magnet on a pivot; but the difficulty has always been to provide a proper channel for carrying off the current after it has acted upon one pole of the magnet. It became evident that no solid conductor would answer the purpose, as it would always be in the way of the magnet during its revolution. This object may, however, be accomplished by employing a magnet of the peculiar shape represented in *fig.* 35, having a double bend in the middle, so that this part is horizontal while the two extremities are kept in a vertical position. The magnet, so shaped, is furnished with an agate cap fixed to the lower side of the middle horizontal portion, resting on a fine point of an upright wire, which is fixed to the base of the apparatus, and upon which the magnet is balanced, so as to allow of its turning freely round. In order to steady its motion, however, a wire loop is attached to the magnet lower down, which embraces the upright wire, and retains that part of the magnet in a position nearly vertical. A small cistern, holding mercury, is also fixed upon the magnet at the middle of its upper side, just above the point of suspension. A bent wire, pointed and amalgamated at the end, passes out from this cistern, and dips into a circular trough of mercury, which is open in the centre, to allow the magnet to pass freely through the opening, and which is supported on a stage, sustained by means of legs connecting it with the base. A wire, proceeding from the interior of this circular cistern, passes out of it, and terminates in a cup with mercury. The electrical current, intended to act exclusively upon the upper half of the magnet, is to be

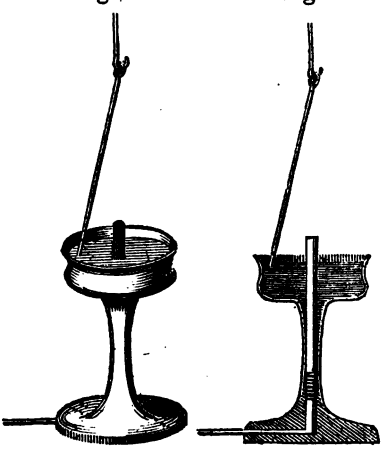
conducted by a vertical wire of sufficient thickness, which is fixed so as just to dip into the small cistern attached to the magnet. Having reached this point, the current is then diverted from its course by the wire which dips into the large cistern, and is thence carried away by the wire which terminates in the cup last described, to such a distance, and in such a direction, as to prevent its acting on the lower pole of the magnet. The magnet will in this manner be made to revolve with great rapidity. It is scarcely necessary to remark, that the direction of the rotation will depend both on the direction of the current and on the nature of the pole which is acted upon; so that reversing either of these conditions will occasion a change in the direction of the rotation. Mr. Watkins describes an apparatus by which these opposite rotations may be exhibited in two magnets at the same time, and by the same current, by placing the poles of the one in a contrary position to those of the other*. But it is unnecessary to dwell upon these obvious combinations of the more simple forms of the experiment.

Fig. 35.



(62.) In the preceding examples, the wire was fixed, and the magnet at liberty to move. But in order to exhibit the revolution of the conducting wire round one of the poles of a magnet, this arrangement must be reversed, that is, the wire must have freedom of motion, and the magnet must be fixed. This Mr. Faraday accomplished by employing the apparatus represented in *fig.* 36. The glass cup holding the mercury is shallow, and has a tubular stem; but instead of being filled with a plug, as was the aperture in the former vessel, a small copper socket is placed in it, and retained there by being fastened by a circular plate below, which is cemented to the glass foot, so that no mercury can pass out by it. This plate is tinned and amalgamated on its lower surface, and stands on another plate and wire, just as in the former apparatus. A small cylindrical magnet is placed in the socket, at any convenient height, and then mercury poured in until it rises so high that nothing but the projecting pole of the magnet is left above its surface at the centre. The forms and relative positions of these parts are seen in the section *fig.* 37. The wire which dips into the mercury, and has its lower end amalgamated, may be suspended to a fixed wire, either by a ball and socket joint, constructed so as to ensure a continuity of metallic conductors, or more simply by means of loops. The best mode of obtaining a perfect contact, is to make the fixed wire terminate in a small cup containing mercury, with its mouth upwards, and to bend the moveable wire into the form of a hook, of which the extremity must be sharpened, and must rest in the mercury on the bottom of the cup, as shown in *fig.* 38. This latter wire, having full liberty to move, revolves round the pole of the magnet which is above the surface of the mercury, with an accelerated velocity, which afterwards

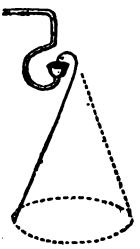
Fig. 36. *Fig.* 37.



* A popular sketch of Electro-magnetism and Electro-dynamics. By Francis Watkins. 1828.

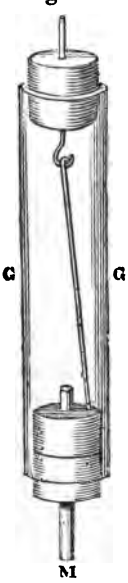
becomes uniform, from the increasing resistance of the fluid; the direction of the motion being determined by the principles already laid down in § 26, and exemplified by *figs.* 9, 10, and 11.

Fig. 38.



(63.) Mr. Faraday also contrived a small apparatus, answering a similar purpose with the last, and in which the wire revolves very rapidly, with a very small voltaic power. It consists of a piece of glass tube, GG, *fig.* 39, the lower end of which is closed by a cork, through which a small piece of soft iron wire is passed, so as to project above and below the cork. A little mercury is then poured in, to form a channel between the iron wire and the glass tube. The upper orifice is also closed by a cork, through which a piece of platinum wire passes, and terminates below by a loop; another piece of wire hangs from this by a loop, and its lower end, which dips a very little way into the mercury, being amalgamated, it is preserved from adhering either to the iron wire or to the glass. When even a feeble voltaic combination is connected with the upper and lower ends of this apparatus, and the pole of a magnet is placed in contact with the external end of the iron wire M, the moveable wire within rapidly rotates round the temporary magnet thus formed by induction at the moment, and by changing either the connexion or the pole of the magnet in contact with the iron, the direction of the motion itself is changed. This apparatus has been made so small as to produce rapid revolutions, by the action of two plates of copper and zinc, containing not more than a square inch of surface each.

Fig. 39.

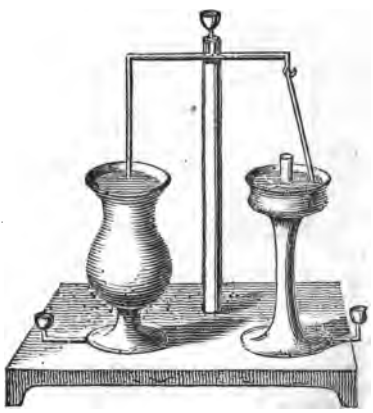


(64.) A still more simple mode of exhibiting the rotation of the wire, is to employ, instead of a pierced cup, a wide and very shallow vessel, as a tea-saucer, for containing the mercury, and to bring a strong magnet underneath as near to it as possible. It may even be placed under the table on which the vessel is laid. Under these circumstances, the revolution of a wire, allowed to dip into the mercury as before, will take place as soon as it is placed in the voltaic circuit. The effect is the same, whether the magnet be held in a horizontal or vertical position, or inclined at any angle, provided the magnet be of sufficient length, so that the influence of the other pole may not act sensibly upon the wire.

(65.) An apparatus was constructed by Mr. Griffiths, for exhibiting, in like manner, the simultaneous revolution of two conducting wires round the opposite poles of magnets. Two copper wires, suspended so as to move freely, were made to dip into a shallow vessel containing mercury, in which were fixed two bar magnets, with their opposite poles raised above the surface. On making the connexion between the battery and the apparatus, the wires revolved round the magnets simultaneously, but in opposite directions*.

(66.) The two forms of electro-magnetic rotation which have now been described, were exhibited at the same

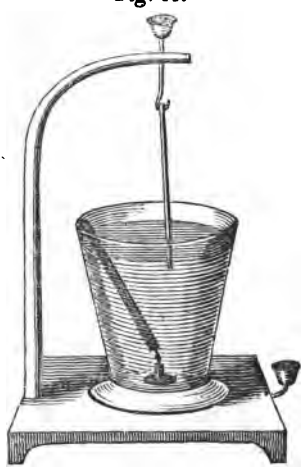
Fig. 40.



* An apparatus of this kind was exhibited by Mr. Barlow, at the London Institution, in 1823, in a course of lectures which he there gave on Electro-magnetism.

time, by an apparatus contrived by Mr. Faraday, in which the cups employed in the two first experiments are both acted upon by the same voltaic battery. This compound apparatus is shown in *fig.* 40. The cups in which the lower wires proceeding from the bottom of each cup respectively terminate, are made to communicate by means of wires with the opposite poles of a battery. The upper wires communicate by a cross wire, supported by an upright pillar fixed in the middle of the stand. The current of electricity, therefore, will ascend through the mercury and wire in one of the cups, and descend in the other, and produce at the same moment a revolving motion of the magnet in the one case, and in the other case, a revolution in the moveable wire. A cup is also placed over the middle of the cross wire for the convenience of sending the electric current in the same direction along both the wires, by making it communicate with one of the poles of the voltaic battery, while the lower cups both communicate with the other pole. The adoption of this arrangement will produce a corresponding change in the direction of one of the rotations.

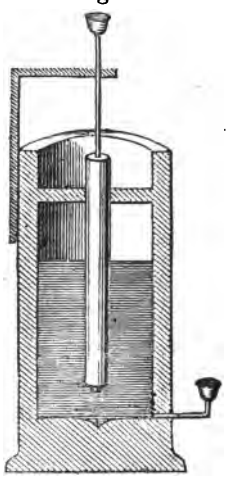
Fig. 41.



(67.) The two phenomena may even be shown in the same vessel, if, in that containing the moveable magnet, *fig.* 33, the wire which dips into the mercury be rendered moveable, as in *fig.* 38, by a mode of suspension adapted to that purpose. The wire and the magnet will then both revolve in the same direction round a common centre of motion, each appearing to pursue and be pursued by the other round the circumference of the circle described by their revolution. (See *fig.* 41.)

(68.) After the discovery of the revolution of a magnet round a conducting wire, and of the wire round a magnet, many attempts were made to obtain the rotation of a magnet, or of a conductor, round their own axes. Ampère was the first who accomplished the former of these objects, which may be effected by the following method:—The cylindrical magnet seen in the section, *fig.* 42, terminates at its lower extremity in a sharp

Fig. 42.



steel point, which rests in the centre of a conical cavity of agate, in the bottom of the vessel, which may be either of glass or wood. The upper end of the magnet is supported in a perpendicular position, by a thin slip of wood, passing across the upper part of the vessel and resting against its sides, having a hole through which the magnet passes freely. A piece of quill is fitted on the upper extremity of the magnet, so as to form a cup or reservoir above it for receiving a small quantity of mercury. Into this mercury is inserted the lower end of a wire which is amalgamated, in order to obtain a perfect metallic contact, while its upper end terminates in a cup holding a globule of mercury, for the purpose of forming a communication with one of the poles of the voltaic battery. The vessel being filled with mercury, so as to cover the lower half of the magnet, the galvanic circuit is com-

pleted by means of a thick copper wire proceeding from the bottom of the vessel, coming out through the side, and terminating in another cup holding a small quantity of mercury, by which a communication may be established with the other pole of the battery. As soon as this connexion is effected, the magnet begins to revolve round its axis with great rapidity, the rotation continuing as long as the connexions with the battery are preserved and the battery retains its power.

(69.) In the original experiment of Ampère, the magnet was allowed to float without support in the mercury, being kept in a vertical position by a weight of platina attached to its lower end. But this addition to the whole mass to be moved occasions a great diminution of effect, so that the apparatus above described gives a much greater velocity of motion with the same galvanic power.

(70.) The same phenomenon has been exhibited in various ways; the principle on which it depends is that the electric current should descend through the upper half of the magnet only, so as to act exclusively on the pole which is situated in that half, and afterwards be diverted from the magnet, and made to pass away in such a direction as that it shall not affect the lower pole of the magnet. In the experiment above related, the electric current, after traversing the upper half of the magnet, passes into the mercury, and being diffused through it, acts in no sensible degree on the lower pole of the magnet, and does not interfere with the rotation produced by its influence on the upper pole. There are several circumstances, however, to be taken into account, in explaining this experiment, which cannot now be easily rendered intelligible, and the notice of which must be reserved for a future part of the Treatise.

(71.) The same object is attained in the following manner, by an apparatus represented in *fig.* 43, and in section in *fig.* 44. A magnet, pointed at both ends, is supported below by an agate cup fixed on a stem rising from the bottom of the stand; while its upper point is lightly pressed upon by a screw, with a milled head, passing through a screwed hole at the top of an arched beam, which forms part of the sustaining frame-work of the apparatus. Near the middle of the magnet, this frame supports a stage in the form of a ring, through the centre of which the magnet passes freely, and carrying a circular cistern of mercury, which also surrounds the magnet, without touching it. A similar cistern of mercury surrounds the lower stem, which supports the agate cup. A copper wire, projecting into the interior of each of these cisterns, passes out through its sides, and, being bent upwards, terminates in a small cup, holding a little mercury, for

Fig. 43.

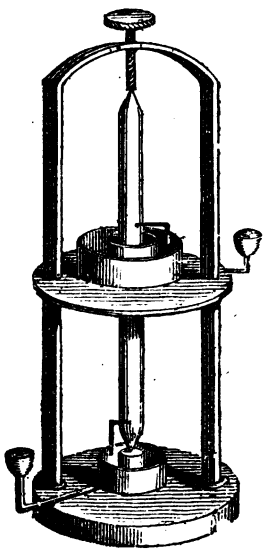
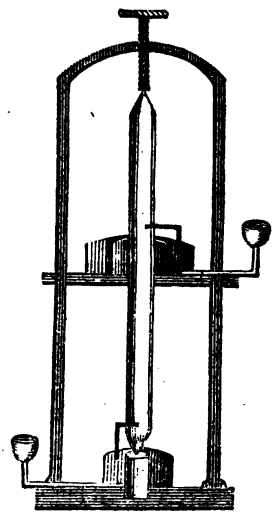


Fig. 44.

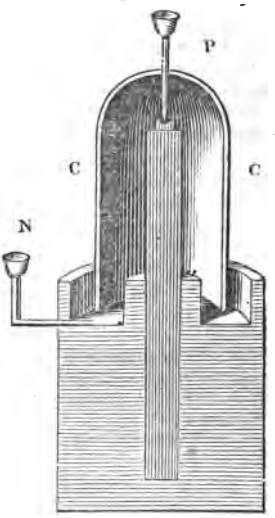


effecting the communication with the voltaic battery by wires, in the usual manner. A small wire, pointed and amalgamated at its end, is affixed to the middle of the magnet, immediately above the cistern, and is bent so as just to dip into the mercury contained in the cistern. A similar wire, proceeding from the lower end of the magnet, is made to dip into the mercury contained in the lower cistern. The lower half only of the magnet being thus made to form part of the galvanic circuit—which is continuous from one cup through the cistern of mercury, the wire belonging to the magnet, the magnet itself, the other wire, the other cistern of mercury, and the wire terminating in the other cup—receives the exclusive influence of the electric current which passes through it, and begins to rotate with considerable velocity round the axis, which is constituted by its upper and lower points of support. The degree of rotatory effect will depend very much on the delicacy of the suspension of the magnet, so that the friction at the points may be as small as possible.

(72.) When the magnet is large, it has been proposed to gain additional rotatory power by directing another electrical current to be supplied from a second battery along the upper half of the magnet, but in a direction contrary to that which passes through the lower pole. This might certainly be effected by removing the milled head of the vertical screw, and supplying its place by a small cup to hold mercury, and by carefully amalgamating the lower end of the screw where it touches the magnet. But since the rotatory force is proportional to the power of the voltaic battery used, it is very doubtful whether the second battery required in this latter method might not be equally efficacious if it were employed in increasing the strength of the first battery, by being joined to it, in the former mode of conducting the experiment.

(73.) Having thus succeeded in making the magnet revolve on its own axis, it next became an object to effect, in like manner, the rotation of a conducting body round its axis. As in the former case it was necessary to apply the electric agency in the interior of the magnet, so in the present instance some means were to be devised for procuring the action of the magnet from the interior of the conducting body: hence it was necessary to discard the wire, and employ in its place a hollow cylinder of metal, capable of receiving the pole of a magnet in its axis. Such an arrangement, which was devised by Mr. Barlow, is exhibited by *fig.* 45, which represents a section of the apparatus. A bar magnet is fixed upright in a solid stand, which has a cavity adapted to receive it, and which also supports a circular trough of mercury, surrounding

Fig. 45.

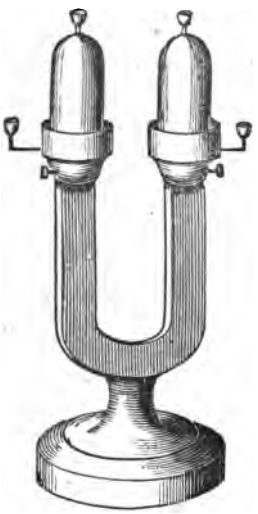


the magnet as in the former instances. C C is a light hollow copper cylinder, the lower edge of which dips into the mercury in the trough; and the upper part is supported by an arch of the same metal, from the middle of which there proceeds a steel-pointed wire, passing downwards so as to rest in an agate cup fixed to the top of the magnet, and also passing upwards and terminating in a small cup P, holding a little mercury, for the purpose of effecting a communication with the voltaic battery. A wire proceeds from the inside of the trough, and passing out, is bent upwards, so as to terminate in another cup with mercury N, for establishing the connexion with the other pole of the battery. It is evident that, in this arrangement, the electric current, which we may suppose to descend from the positive wire of the battery introduced into the cup P, being prevented from passing into the magnet by the interposition of the agate cup, can find no other channel than the copper cylinder, down the sides of which

it will descend into the mercury in the trough, and thence, passing out by the wire below, will proceed through the cup N, and be received by the wire communicating with the negative end of the battery. The cylinder may therefore be regarded as consisting of a collection of parallel wires, each of which receives from the pole of the magnet placed in the interior an impulse to move in a direction parallel to itself.

Those on opposite sides of the magnet will be urged to move in opposite directions; but as their forces act on opposite sides of the axis of motion, they will all concur in their rotatory effect. The whole cylinder is accordingly found to commence revolving as soon as the

Fig. 46 *.



electric current is sent through it; and the resistance it meets with being slight, its velocity soon becomes very considerable. After what has formerly been said, it is scarcely necessary to add, that the course of its motion is from left to right, or the same with that of the hands of a watch, when the electric current is descending along the cylinder, and when the enclosed part of the magnet is its north pole.

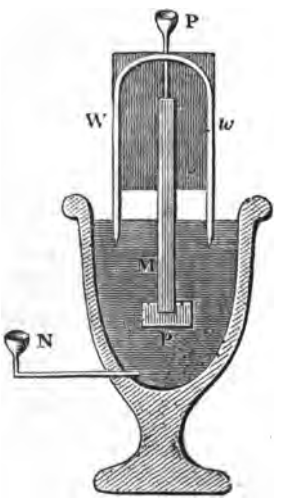
(74.) The motion is reversed when either of these conditions is reversed. This may be conveniently exemplified in the two poles of the same magnet by employing a horse-shoe magnet, supported vertically in a stand, as shown in *fig.* 46. Two wooden circular troughs are fixed upon the arms of the magnet, and secured by binding screws. These troughs contain the mercury into which the lower margins of the hollow cylinders dip. The upper part of each cylinder is formed into a hemispherical cup, which is traversed in the middle by a pointed wire, resting below in a small cavity in the centre of the extremity of the magnet contained within the cylinder, and having at its upper end a small cup to hold mercury. Two other cups, also containing a small quantity of mercury, are supported upon the external ends of bent wires, which pass through the sides of the circular troughs into the mercury contained in them. Thus a continuous metallic communication is established from one cup to the other, on each side, through each cylinder which surrounds the different poles of the magnet. If a stream of electricity from a voltaic battery be made to pass in the same direction in both the cylinders, they will revolve in contrary directions, being acted upon in an opposite manner by the two poles which they surround. But if the two upper cups be united by a short wire dipping its two ends in the mercury they contain, and the lower cups be connected, the one with the positive, and the other with the negative poles of the battery, the same stream will traverse both sides of the apparatus, passing upwards in one cylinder, and downwards in the other; and the rotations thence arising will now, from the contrary influences of the two poles, be in the same direction in both the cylinders.

(75.) The rotation of a conducting body round its own axis, as exhibited in the experiments just related (§ 73), throws considerable light upon the circumstances of the experiment before described, in which a magnet was made to rotate about its axis; for the explanation of that experiment will very much depend upon the course which we suppose taken by the electrical current during its passage through the magnet. If we supposed it to pass through the interior of the magnet, that is along the axis, and parts adjacent to it, it would occasion rotation by its influence on the parts of the magnet that are situated nearer to the surface, and further from the axis. On the other hand, if we suppose the course of the electric current to be nearly superficial, then it will

* See Mr. Watkins's Sketch, p 74.

itself be influenced by the polarity of those portions of the magnet which lie near the axis, and the rotatory tendency impressed upon it will produce the rotation of the magnet, which will, of course, be carried along with it. On the latter supposition, it will correspond, in all its circumstances, with the experiment § 73, in which the conducting body is urged to rotate by the influence of a magnetic pole situated within it: excepting only, that in the former case the magnet and the conducting body were one and the same, while in the latter they were different and separate. Mr. Faraday has shown, however, that the circumstance of the magnet and conductor being immoveably joined together makes no difference in the results. Thus let the magnet M, represented in section, *fig.* 47, be loaded at its lower end with a platina weight, and fixed at its upper end on a piece of card or wood, having two branches of a strong wire, W W, descending from its upper edge

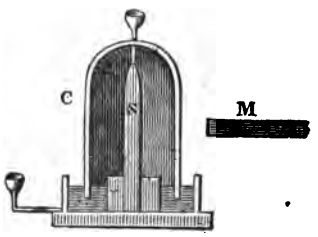
Fig. 47.



along its two vertical edges, and terminating below in points: so that the whole may float, in a vertical position, in a vessel full of mercury, from the bottom of which a wire proceeds, supporting the cup N; another cup, P, being placed upon the upper edge of the wires W W. The whole moveable part of this apparatus will rotate by the transmission of an electric current through the wires, on making the proper communications with a voltaic battery by means of the two cups containing mercury. This experiment is important, inasmuch as it appears to show that the action is the same, whether the magnet from which it proceeds be in motion or at rest. We shall have occasion, however, in a future part of this treatise, to point out another mode of explanation arising out of a different view of the subject.

(77.) On the other hand, when a hollow cylinder of metal, balanced on a point on the upper end of a vertical axis of wood, and its lower edge dipping into a trough of mercury, is acted upon by one of the poles of a magnet placed on the outside, and brought near it, as shown in the section *fig.* 48, where M is the magnet applied to the cylinder C, balanced in the wooden stand S, the rotatory force is very feeble, compared with that which takes place when the mag-

Fig. 48.



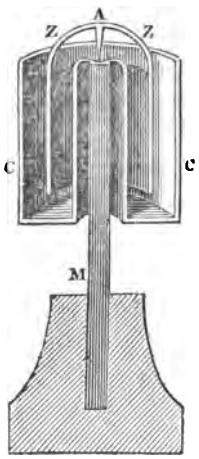
net acts from within the cylinder. The reason is, that the tendencies to motion of those portions of the moveable conductor which are most remote from the magnet, and of those which are nearest to it, are in opposite directions with respect to the centre of motion; and, if the conductor be cylindrical, and the current equally distributed on every side of it, must always exactly counterbalance one another. This will be evident when it is considered that, although these latter portions are, in consequence of their greater proximity to the magnet, acted upon more strongly, this advantage is compensated by the greater extent of the portion on the remote side, which is acted upon more feebly. But this equilibrium will not obtain if, as generally happens, the electric current be unequally distributed. If, for instance, it pass along one side only, the cylinder will revolve when the magnet is brought opposite to it on that side.

(78.) It appears, by the result of the experiment related in § 73, that the electro-magnetic influence of the conductor takes place equally when the current of electricity is diffused over a considerable surface, as when it is concentrated in a slender wire. The effects will, of course, be weaker in proportion as it is diffused; but when the whole of these scattered forces can be brought to bear in the production of any effect, the amount will be the same as when they are concentrated in a smaller space. Thus every filament of which the cylinders in these experiments may be supposed to be resolved, conducts its respective portion of the electric current, and contributes its share in the production of one common effect, namely, the revolution of the cylinder.

In like manner it has been found that the stream of electricity, which is passing through the voltaic battery itself from its negative to its positive pole, exhibits the same electro-magnetic properties that it does while passing along the wire which completes the circuit by connecting the two poles; for a magnetic needle placed in the vicinity of the battery, and in circumstances equally favourable to the action of the current, will be affected in the same way as it is by the wire itself. Now as all action implies a corresponding and equal reaction, it is reasonable to infer that, as the battery produces motion in the magnet, so the magnet might be made to move the battery, if a sufficiently delicate suspension could be contrived for the latter, so as to render its motion sensible. This could scarcely be effected with a compound battery of any size: but by reducing it to a single plate, making it as light as possible, and supporting it on a single point, in the way in which the cylinder was sustained in the last experiment, this object has been accomplished by Ampère.

(79.) The apparatus he employed for this purpose is represented in section, in *fig.* 49. It consists of a double cylinder of copper, C C, about two inches and a half in diameter, and the same in height, closed at the bottom, so as to form a vessel capable of holding diluted acid. The whole is supported by an arched plate of metal, which passes across the upper orifice of the inner cylinder on the upper end of a strong magnet, M, which is introduced through the middle of the cylinder. A cylinder of zinc, Z Z, made as light as possible, and supported by an arched wire, A, having a steel point proceeding downwards from the middle of its curvature, is introduced between the two plates of the double copper cylinder, so that the steel point

Fig. 49.



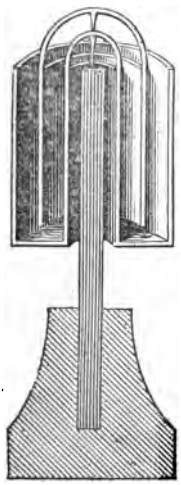
may rest upon the arched plate of the inner cylinder, and remain balanced in this position. On introducing diluted acid into the copper vessel, a galvanic action immediately commences; the electric current passing from the zinc to the acid, and ascending from the copper through the pivot back again to the zinc. Hence the zinc is in the situation of a conductor conveying a stream of electricity downwards, and under the influence of the magnetic pole which it surrounds. It will consequently revolve with an accelerated motion, which is at length rendered uniform by the friction of the fluid.

Mr. Barlow states that he has frequently, with this simple apparatus, produced a velocity of one hundred and twenty revolutions in a minute.

(80.) The theory just explained is prettily illustrated by an addition to the preceding apparatus which was made by Mr. J. Marsh; and which consists in having a second steel point fixed underneath the upper part of the arch which sustains the copper cylinder: the copper vessel may, by means of this point, be itself balanced on the top of the magnet, while the zinc cylindrical plate is balanced on the former; and each may thus turn round its own centre independently of the other. This arrangement

is represented in the section *fig.* 50. As the electric current ascends in the copper cylinder, while it descends along the zinc, the former will be urged by the magnet in its interior, to revolve in a direction contrary to the motion of the zinc cylinder. The velocity of the copper vessel is, however, much smaller than that of the zinc, not only from its greater weight, and from carrying besides the whole quantity of acid, but also from the friction of its pivot being increased by the weight of the zinc plate which that pivot has to support. In this double revolution, also, the velocity of the zinc plate is further retarded by the increased resistance it meets with from the fluid which is moving in a contrary direction.

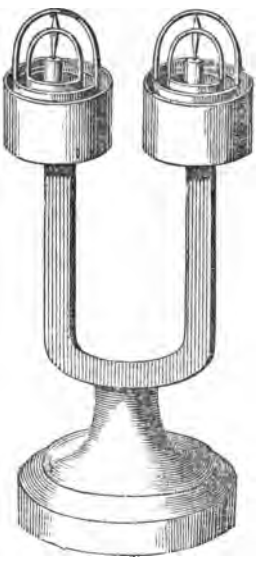
Fig. 50.



(81.) Mr. Watkins has applied an apparatus of this kind to each of the poles of a horse-shoe magnet, firmly fixed in a metal stand at its bent part, as shewn in *fig.* 51. The upper ends of the magnet are furnished with agate cups for receiving the steel points on which the apparatus is supported. The wire itself traverses the arch affixed to the copper vessel, and terminates in a point at its upper extremity also, so that the arch connected with the zinc plate rests upon it. When the apparatus is brought into action by charging the vessels with acid, the four cylinders are seen to revolve on their axes, the two copper vessels turning in opposite directions, and the two zinc cylinders turning in directions opposite to these, and of course also contrary to each other: the rapidity of their revolutions, depending on the power of the magnet, on the strength of the diluted acid, and on the delicacy of their suspension.

(82.) Horse-shoe magnets may also be conveniently employed for combining the effects of both poles in giving motion to a conducting wire. The operation of the two poles being in contrary directions at their opposite sides, they will, on the other hand, conspire in producing the same effect upon a wire placed between them. Thus each

Fig. 51.



of the conducting wires $p\,n$, $p'\,n'$, *figs.* 52, 53, in which the electric current is

Fig. 52.

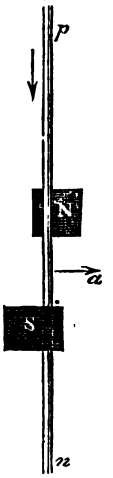
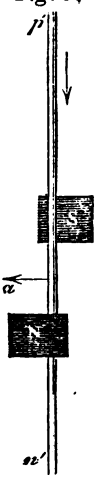


Fig. 53



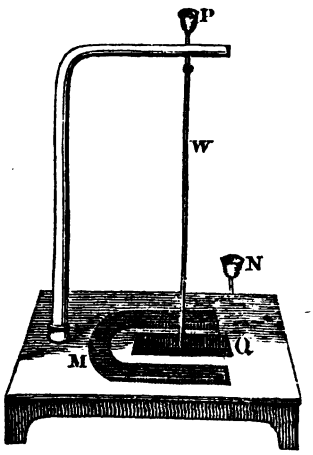
descending from p to s, when placed between the magnetic poles N and S, the former being north, and the latter

south, and which, for the sake of illustration, we may conceive to be insulated, will be urged by their united influence to move parallel to itself, in the direction denoted by the arrows *a*, *a*, in the figures; that is, from right to left, if the north pole be behind, and the south pole before, as in *fig.* 52; and from left to right, if the poles are in a contrary position, as in *fig.* 53.

(83.) Several amusing experiments have been contrived, in which vibratory or rotatory motions of different kinds are obtained by various applications of this principle.

The following is the invention of Mr. Marsh. A conducting platina wire W, *fig.* 54, is suspended by a loop from a

Fig. 54.

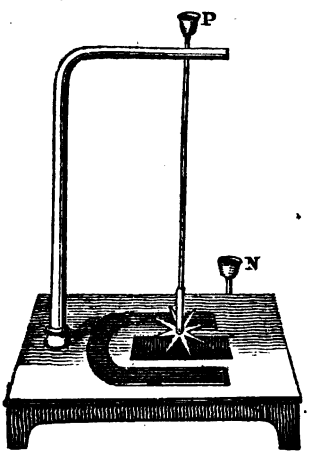


metallic hook at the lower end of another wire, which is fixed to the end of the arm of a stand; and which supports above the small cup P, to contain mercury. The lower end of the platina wire, which thus hangs freely, dips into a small cistern of mercury, Q, formed out of the wooden base, and is just midway between the two poles of a horse-shoe mag et, M, laid flat upon the same base.

The mercury in the trough is placed in electrical continuity with another cup, N, by means of a wire passing out from the side, and supporting the cup. On making a communication with the two ends of the voltaic battery by means of these cups, the current passing along the loose platina wire, being influenced by the magnet, urges the wire either forwards towards Q, or backwards towards M, according to the position of the poles, and the direction of the current. In either case it is thrown out of the mercury; and the circuit being thus broken, the effect ceases, until the wire falls back again by its own weight into the mercury; when the current being re-established, the same influence is again exerted, the phenomenon is repeated, and the wire exhibits a quick succession of vibratory motions.

(84.) This reciprocating movement of the wire may be converted into one of rotation, by adapting, as proposed by Mr. Barlow, a spur-wheel, as shewn in *fig.* 55, to the lower part of the upright wire, which must then be firmly fixed to the arm of the pillar. The wheel, being constructed so as to turn round freely, will revolve with great rapidity as soon as the contacts are made with the battery: for this purpose, however, the wheel must dip so far into the mercury, as that each of the rays shall touch the surface before the preceding ray has quitted the mercury. The direction of the motion depends, of course, on the same circumstances as were before mentioned: Mr. Barlow observes, however, that in general the experiment succeeds best when the wheel revolves inwards.

Fig. 55.

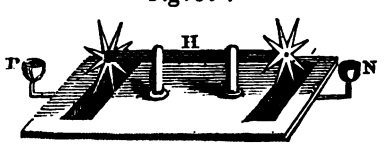


(85.) But it is not necessary to divide the wheel into rays in order to produce the effect above described; for a circular metallic disc substituted for the spur-wheel will revolve equally well, when it is traversed by an electrical current passing into mercury between the poles of a horse-shoe magnet. For

this purpose the circumference of the disc should merely touch the mercury in the trough. It is necessary also that it be well amalgamated; this is best done by removing it from its centres, and cleansing the edge thoroughly by a file, and then dipping a piece of wire into nitrate of mercury, and taking up with it a portion of the mercury contained in the nitrate, transferring it to the edge of the disc, by rubbing the wire, coated with mercury, round it. This substitution of a continuous for a divided disc was suggested by Mr. Sturgeon.

(86.) The same current may be employed to turn two wheels with radii, by disposing them in the manner shewn in *fig.* 56, at the extremities of a horizontal wire which is supported on two pillars arising from the stand, and which serve as the common axis of the wheels.

Fig. 56*.



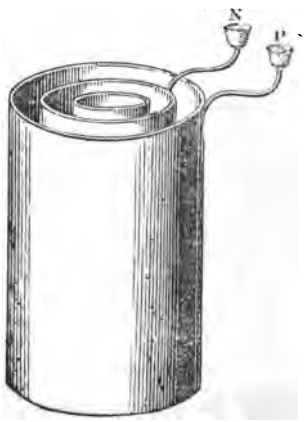
The lower ends of the rays dip into troughs of mercury, each lying between the poles of horse-shoe magnets. Each trough has its respective wire and cup P and N for making communications with the voltaic battery. The current passing from the one cup to the mercury in the trough on the same side, rises along the radius, which dips into it, and passing along the axis, arrives at the other wheel; then descending along its radius into the mercury, it makes its exit by the cup on that side. The electric currents, moving in opposite directions in the two wheels, require a contrary disposition of the poles of the two magnets by which they are to be acted upon: that is, the poles of the two magnets that are within the wheels must both be of the same kind; as must also be those that are exterior to them. The velocity of the wheels thus revolving by the united action of both magnets is very great.

(86.) The experiments on electro-magnetic rotation we have described, do not require for their successful performance a voltaic battery of any considerable size or power. If the magnets be sufficiently energetic, nothing more will be required than a single pair of plates. The most convenient form of a battery of this kind, is that described by Mr. Watkins, and which is represented in *fig.* 57.

It consists of a double cylindrical vessel made of thin copper, with a bottom of the same metal. A plate of zinc rolled into a cylinder, of a diameter intermediate between those of the copper cylinder, is introduced between them, but prevented from touching them in any part, by three wooden feet placed at the bottom of the vessel, and also by pieces of wood interposed as wedges between the sides.

A copper wire is soldered to the inside of the top of the outer copper cylinder, and

Fig. 57.



has a small cup P, fixed at its extremity; the wire passing through the bottom of the cup in order to come in contact with the mercury placed in it. Another and similar wire N, is also affixed to the upper edge of the zinc cylinder, likewise terminating in a cup which holds mercury. The battery is charged by filling the copper vessel with diluted acid; and the electric current, which is the effect of the voltaic action thence arising, may be easily transmitted to the apparatus where it is wanted, by means of two bent copper conducting wires, one end of the one being inserted into the mercury contained in the cup proceeding from the zinc cylinder, and the other in the cup fixed to the copper cylinder; while the other ends are immersed in the mercury placed in the cups attached to the apparatus. The current may be arrested or renewed at

* The engraver has forgotten to insert the horse-shoe magnets in this wood-cut. They should have been placed as the one in fig. 55.

any moment, by removing one end of either connecting wire from its cup, or by replacing it. The direction of the current may also be readily changed, by merely exchanging the situation of the wires in two of the cups. The extremities of the connecting wires should be made perfectly bright, and the ends of the wire arms which support the cups and enter the mercury in them, ought also to be in a similar state, so that a perfect metallic contact may be preserved.

(87.) In making electro-magnetic experiments, where numerous repetitions of contacts between wires are often required, it is extremely useful, if these wires are of copper, to rub the ends over with a little nitrate of mercury; an amalgam is thus formed on the surface of the copper, which does not oxidate or become dirty, as copper itself does, but remains bright, and fit for voltaic contact for a considerable length of time. For this useful manipulation we are indebted to Mr. Faraday.

(88.) The movement of currents by the influence of the pole of a magnet may be exemplified in fluid as well as in solid conductors. Thus mercury, while conducting a current of electricity, is made to exhibit these motions with the greatest facility. By immersing the points of the positive and negative wires into a shallow basin containing mercury, a magnet held either above or below the line of communication will cause the mercury to revolve round the points from which the currents diverge. This motion may be rendered more evident by covering the mercury with a very dilute acid solution, which occasions the disengagement of bubbles of air which are moved along with the mercury. The same phenomenon may also be exhibited in the following manner. If the positive wire terminate in a steel point which is dipped into mercury contained in a shallow basin, so as to convey into it an electric current, which, passing in radiating lines through the mercury, is received by a copper ring surrounding the steel point, and so tranferred to the negative pole,—by placing the pole of a strong magnet underneath the basin immediately below the steel-pointed wire, the mercury will be seen to revolve rapidly in a vortex round the point from which the currents diverge. The revolution is in the contrary direction, if either the direction of the current be reversed, or the opposite pole of the magnet be applied.

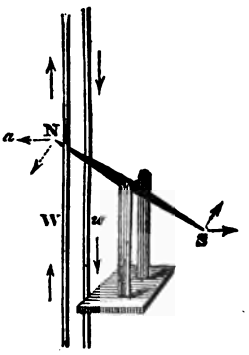
(89.) Sir Humphry Davy found that the arched stream of electrical light which extends between two points of charcoal that are placed in the voltaic circuit, as described in the Treatise on GALVANISM, § 27, is thrown into a rapid rotatory motion by the action of the pole of a magnet placed near it*.

CHAPTER VII.

Concentration of Effects.

(90.) We have already seen, § 82, that when a conducting wire is placed between the contrary poles of a magnet, it receives a similar influence from these poles, and is urged to move in one particular direction by the united force of both. A similar combination of powers will occur when the pole of a magnet is placed between two parallel conducting wires, in which the electric currents are moving in opposite directions. Thus, if the needle N S, *fig.* 58, balanced as a

Fig. 58.



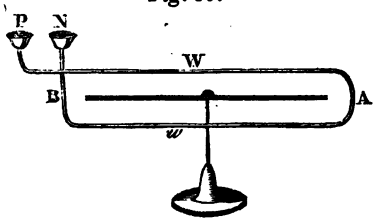
dipping needle, be placed between the two wires W, *w*, in the former of which the current is ascending, and in the latter descending, the north pole of the needle will be urged in the same direction, denoted by the arrow *a*, by both the wires, in a plane parallel to the wires, and at right angles to the plane in which they are both situated. The south pole will also be urged in the contrary direction by both wires; and the needle will, by the combination of these forces, have a strong tendency to turn upon its centre.

(91.) If the wires be joined together at either end, or, what comes to the same thing, if a continuous wire be bent back upon itself, an electric current

* Philosophical Transactions for 1821, p. 427.

sent through such a wire will affect a needle placed between its two branches with twice the force that a single wire would have exerted. This effect may be exhibited by the following simple apparatus, represented in *fig.* 59; where the two cups terminating the bent wire W A *w* B which passes above and be-

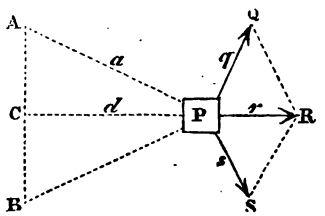
Fig. 59.



low a magnetic needle balanced on a point, enable us to transmit through it an electric current in any direction we please. This current, moving in opposite directions in the upper and lower horizontal portions of the wire, will conspire, in both cases, to deflect it from its natural position in the same direction, and to bring it into a position nearer to a right angle to the plane of the wires.

(92.) The force with which each pole is impelled in a line at right angles to the plane in which the wires are situated, is directly as the intensity of the current, (supposing it to be equal in both wires,) and directly as the length of the interval between the wires, and also inversely as the square of the distance of the pole from the wires. This will appear from the following considerations. Let A and B represent the sections of two wires passing perpendicularly through the plane of the figure, C being

Fig. 60.



the middle point of the line A B, which constitutes the interval between them. Let the magnetic pole P be placed at various distances along the line C R, perpendicular to A B, and consequently perpendicular to the vertical plane which passes through A B, and comprehends the two wires. Supposing the wires to be of indefinite length; the law of action is such, that the intensity of the tangential force exerted on the pole P by the wire A, is inversely as the distance A P, which we shall call a, and is in the direction P Q, perpendicular to A P. In like manner, the wire B exerts upon the pole P, a force in the direction of P S, and which, on the supposition of an equal intensity in the two currents, is equal to the former force. If these two forces be represented by the lines P Q and P S, which we shall call q and s, the resultant force will be represented by the diagonal P R of the parallelogram, having P Q and P S for its sides. Calling PR, r, and AB, i, we have this proportion,

$$a : i :: q \quad r,$$

that is,

$$r = \frac{i\,q}{a};$$

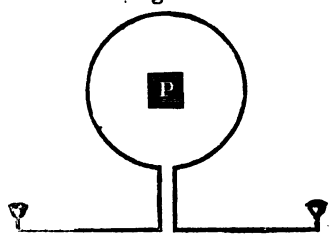
but, in different positions of P along the line C R, q will vary inversely as a; and therefore r will be as $\frac{i}{a^2}$; that is, the force by which the pole P is urged in the direction of the line C R, by the conjoined action of the two wires A and B, varies, in different situations in that line, inversely as the square of its distance from either of the wires, and directly as the length of the interval between the wires.

(93.) In order to estimate the rotatory force exerted on a needle constrained to move round a fixed axis in a plane perpendicular to that of the wires, as in the examples above given, §§ 90, 91; it will be necessary to resolve the force above found into one acting in the direction of the tangent to the circumference of rotation; that is, to reduce it in the proportion of radius to the cosine of the angle which the needle forms with the plane of the wires.

(94.) In the situation of the magnet represented in *fig.* 59, where the wires, instead of extending indefinitely in the horizontal direction, enclose the magnet also on the sides, the influence of the lateral portions A and B require to be taken into account in estimating the effect produced. A little consideration will satisfy us that the action of these parts concur with those of the horizontal portions in giving the same directive tendency to the needle; and that, in fact, if we suppose the wire to be bent

into a circular form, as shewn in *fig.* 61, the magnetic pole P, placed in the centre

Fig. 61.



of the circle, or in a line passing through that centre, and at right angles to its plane, would be impelled in one uniform direction by an electric current transmitted through the wire, in every part of its course along that circular bend.

(95.) Supposing it were possible for the current to move in a perfect circle, its direction being that indicated by the arrows in figures 62 and 63, the north pole of a magnet placed in its centre would move to the right, and the south

Fig. 62.

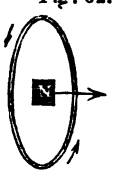
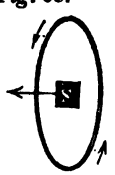


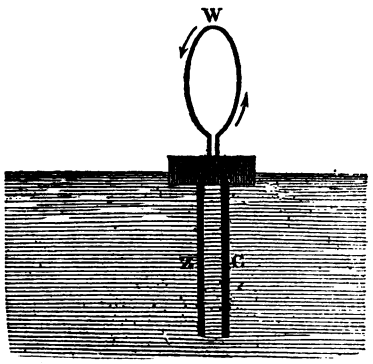
Fig. 63.



pole to the left; as shewn by the arrows at N and S. If the north pole of a magnet, therefore, were presented to the right hand side of this circular current, it would tend to move away from it, having the appearance of being repelled: and since a similar and reciprocal action takes place between the magnetic pole and the electric current, the latter, together with the wire which conveys it, will, if at liberty to move, recede from the magnet, or appear to be repelled by it. Just the contrary would happen if the south pole of a magnet were presented on the same side; that is, there would be the appearance of a mutual attraction between them. But when either of these poles is presented on the other side of the plane of the circular current, effects of an opposite kind are produced: the north pole appears to attract, and the south pole to repel. If the north pole, which thus appears to attract on one side, be brought nearer and nearer to the plane of the circle, the apparent attraction goes on increasing, till it reaches that plane; but the moment it passes through it and comes on the other side, a repulsion equally strong with the former attraction commences; gradually diminishing as the distance from the plane increases.

(96.) This hypothetical case may in some measure be realized in a very ingenious apparatus invented by M. De la Rive *, and which is shown in *fig.* 64. It consists of a small galvanic battery, formed by a pair of zinc and copper plates, Z and C, attached to a cork of

Fig. 64.



sufficient size to enable the whole apparatus to float on the acidulated water which is to act upon the zinc. Each of the metallic plates is about half an inch wide, and extends nearly two inches below the cork, through which its upper end is made to pass. A piece of copper wire, W, covered with silk thread, is affixed to the copper plate, and passing upwards through the cork, is bent into the form of a circle of about an inch in diameter, so that the other end returns into the cork and may be soldered to the plate of zinc. In the galvanic circuit which is thus formed by the acid and the plates of zinc and copper connected by the wire, an electric current is determined from the copper plate, along the circular wire, to the zinc plate, as shown by the arrows; and the mobility of the floating apparatus affords the best opportunity of exhibiting all the effects of the attractive and repulsive tendencies we have just been describing, when a magnet is brought near it on either side. It is proper to remark that the instrument is rendered more powerful by causing the wire to

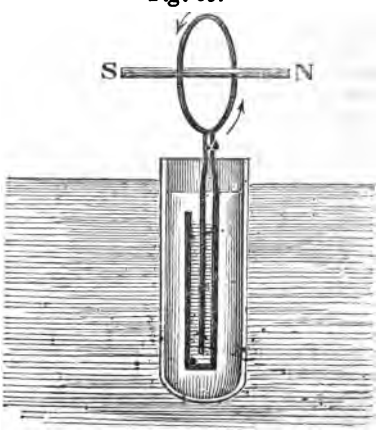
* This apparatus is described in the Bibliothèque Universel, vol. xvi. p. 201; and in the Quarterly Journal of Science vol. xii. p. 184.

make five or six turns in the circle, and then tying the coils together so as to form a ring, which being thus composed of a number of concentric circles, the action of each is combined, and the power as it were multiplied by the number of turns.

(97.) This difference in the effects which the two sides of the plane of the ring in this instrument have on the same pole of a magnet, presents a very striking phenomenon, and exhibits a strong analogy with the magnet itself. We may in fact consider it as a flat magnet, having its two poles in the centre of it, two surfaces, the one on one side, and the other on the other: so that if, on looking at one of these surfaces, the current is moving in the same direction as the hands of a watch move when we face the dial, then the side on which we are looking may be regarded as having the properties of the *south pole;* and the other side that of the *north pole.* The former attracts and is attracted by the north pole of a magnet; the latter attracts and is attracted by the south pole, and *vice versâ.*

(98.) A very curious phenomenon is seen when a magnet is presented horizontally to the vertical electro-magnetic ring of M. De la Rive; supposing the magnet to be sufficiently slender to pass easily through the ring. If the pole be presented to it on the side where attraction takes place, the ring will move towards it, till it arrives at the pole, and then proceeds onwards in the same course, the magnet being held in the axis of the ring, till it reaches the middle of the magnet; but there it seems inclined to stop; and then, after a few oscillations, it settles, as in a position of equilibrium: for if purposely displaced by bringing it forwards towards the other pole, it returns with a force which shows that it is repelled from that other pole. Let us now withdraw the magnet, and turning it half round, so that its poles are in directions the reverse of what they were at first, and holding the ring in one hand, let us again introduce the magnet into it with the other hand, until it is half-way through. Under these circumstances it is just possible that we may have brought it into such a situation as that the ring may again be in equilibrium, undetermined in what direction to move; but the slightest change in this position causes it to move with an accelerated velocity towards that pole which is nearest to it; and getting entirely clear of the magnet, it is projected to a considerable distance from it. At length, however, it stops, and, gradually turning round, presents the opposite face to the magnet; attraction now takes place, and the ring returns to the magnet with a force equal to that with which it had before fled from it; and passing again over its pole, finally rests in its position of equilibrium, encircling the middle, or what may be termed the equator of the magnet. In the former position it was equally attracted by the two poles of the magnet; in the latter it is equally repelled: and accordingly the first was an unstable, and the last a stable equilibrium. The ring is represented in this last situation in *fig.* 65, surrounding the middle of the magnet, S, N.

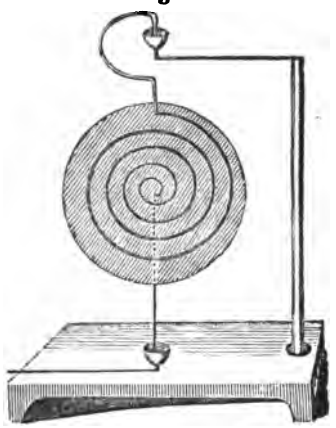
Fig. 65.



(99) M. De la Rive's apparatus may be constructed so as not to require the liquid in which it floats to consist of the acid; for if the copper plates be double, and pass round the zinc plate, so as to form a cell capable of holding the acid and the zinc plate, the whole combination may be enclosed in a glass cylinder, which will enable it to float in water. Both the surfaces of the zinc are thus opposed to a surface of copper, as in the construction proposed by Dr. Wollaston. (See Galvanism, § 18.) This addition was first suggested by Mr. Marsh, and is represented in the preceding figure (65). The tube for this purpose may be made out of the neck of a Florence flask

(100.) The magnetic properties of circular conductors may be exhibited in a striking manner by bending the wire

Fig. 66.

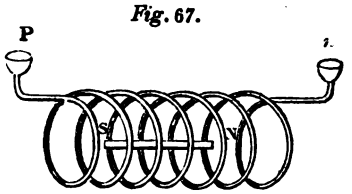


into the form of a spiral, see *fig.* 66. The upper end of the wire should be bent downwards and terminate in a point, for the purpose of being inserted in a cup containing mercury, which communicates by a wire with one of the poles of the Voltaic battery. The coils of the wire may be either secured from contact by being wrapped round with silk thread, or may be attached to one surface of a card, while the wire which proceeds from the centre of the coil passes through the card, and descends in a straight line on the opposite side, so as to rest by its pointed extremity on the inside of another cup, also containing mercury, in order to form a communication with the other pole of the battery. A coil of this description, all the successive coils of which conspire together in producing the opposite polarities on its two sides, imitates still more decidedly the effects of a magnet, whose poles might be supposed to be situated in the centre of each disc.

(101.) A still closer imitation of a magnet is obtained by making the turns of the wire not in the same plane, as in the spiral just described, but on a cylindrical surface, like the turns of a corkscrew; a figure which mathematicians have termed a *helix:* an arrangement which possesses many remarkable properties, both as regards its interior and its exterior action.

In *fig.* 67, the several turns of the helix are represented as separated to a distance from each other, in order that the direction of the turns, and the position of a magnet placed in the axis may be distinctly seen. The electro-magnetic influence exerted by each turn is, as we have seen, to urge the north

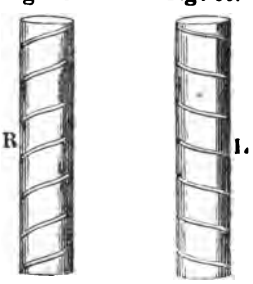
Fig. 67.



pole of a magnet placed in its axis, to move in one direction along that axis, and the south pole in the contrary direction. The force thus exerted is, of course, multiplied in degree and increased in extent, by each repetition of the turns of the wire; and a magnetic needle in every part of the interior of the helix will have a powerful tendency to place itself in the axis, and to turn its poles in a manner conformable to the nature of the force that is in operation.

(102.) Now this force depends on two circumstances: first, the direction of the current with reference to the axis of the helix; and, secondly, the direction of the circumvolutions which compose it. It is well known that screws are of two kinds, distinguished as right-handed or left-handed screws. In the former, as shown in *fig.* 68, the turns proceed

Fig. 68. *Fig.* 69.

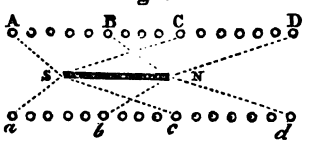


downwards, (if the screw be placed with its axis vertical) from right to left, on that side which is next to the spectator. In the left-handed screw (see *fig.* 69), the turns proceed in the contrary direction. Now the magnetic polarity of the electric helix, which is exerted in the space it encircles, depends on the direction in which the current is moving with reference to a plane at right angles to the axis; for if the current be descending on the side next to the spectator, (in the horizontal helix, *fig.* 67,) the north pole of a magnet in the axis will

be determined to the right, and the south pole to the left; and this tendency will be given in the right-handed helix if the current be transmitted through it from left to right; but in the left-handed helix from right to left. It requires but a slight effort of attention to these particulars to perceive the influence they have on the phenomena; yet unless this effort be made mistakes may easily be committed.

(103.) When the needle lies exactly in the middle of the axis of the helix, the opposite forces which impel the two poles in contrary directions, derived from each coil of the wire, exactly balance one another, and the needle remains in equilibrium. When disturbed from this position, by being pushed nearer to one end, the forces derived from the turns of the wire collectively act with more power upon that pole which is nearest to the middle point of the axis, both because they are nearer, and because they act less obliquely. These forces will, therefore, prevail over those that urge the more distant pole in the contrary direction; and the magnet will be brought back to its former position in the middle of the axis. This is illustrated in *fig.* 70, which represents a section of the helix; S N being the

Fig. 70.

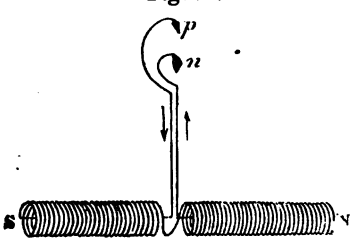


position of the magnet, a little to one side of the middle point of the axis. It will be evident that, in as far as the pole S is acted upon by forces derived from the turns of the wire situated between A *a* and C *c*, its tendency to move outwards is exactly balanced by the forces arising from the action of the wires between B *b* and D *d* upon the pole N, urging it in the contrary direction; because these wires have exactly the same relative situations to these respective poles. But the pole N is besides acted upon by all the wires that are situated between B *b*, and the end A *a*, and the pole S by all those situated between C *c* and D *d*. These two actions are in opposite directions; but the former is more powerful than the latter; first, because the wires between A *a* and B *b* are nearer to N, than those between C *c* and D *d* are to S; and secondly, because they act with less obliquity: they will therefore impel the whole magnet towards the middle of the axis.

(104.) So powerful is the action of a helix of this description, that if a small magnetized needle, or bar, be placed within it, so as to rest upon the lower portions of the wire, the moment the connexion is made with the Voltaic battery, so that the electric current circulates through the wires, the needle is seen to start up, and place itself in the axis, remaining suspended in the air in opposition to the force of gravity. This will even take place in a vertical position of the helix, presenting the singular spectacle of a heavy body raised by an invisible power, and maintained, like the fabled statue of Theamides, in a situation totally free from any material connexion and support.

(105.) The magnetic actions of a helix at its two extremities, and at some distance beyond them, agree with those of the sides of a single circle, or spiral coil already explained; one end having properties similar to the north, and the other to the south pole of a magnet. But the imitation may be rendered still more complete if the two portions of the wire which has formed the helix, and are situated at its two extremities, be bent back as shown in *fig.* 71, at N, S, so as to return in a straight course along the axis till they arrive at the middle point, where they are again bent at right angles, in order to pass out between the coils, rising parallel to one

Fig. 71.

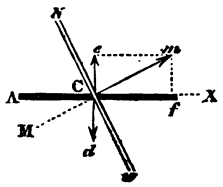


another, and terminating in points for the purpose of suspension in cups, as already described in the case of the spiral wire. Sometimes one of these wires, instead of being bent upwards, is made to descend vertically, and terminate in a sharp point below, where it is inserted into a cup.

(106.) What constitutes the peculiar excellence of this arrangement—which

nas been termed by Ampère an *electro-dynamic cylinder*, with a view to its assimilation with the condition of a magnetic cylinder—is this; that whatever magnetic action the turns of the heliacal part of the wire may have in a longitudinal direction, (that is parallel to the axis,) is counterbalanced by the contrary action of the returning wire. For the direction of each of the heliacal portions of the wire, that of W *w*, for instance, *fig.* 72, being necessarily somewhat oblique, and the magnetic force it exerts being along M *m*, at right angles

Fig. 72.

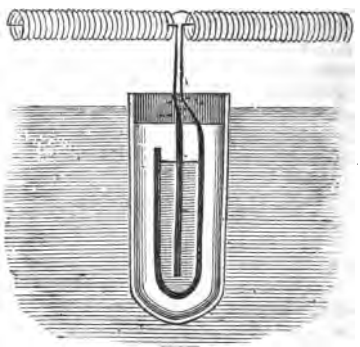


to that direction, the whole of the force is not exerted in the direction of the axis A X, but only that part of it represented by C *f*, while another part, C *e*, is directed at right angles to the axis. But that portion of the straight wire which passes along the axis, and corresponds in its length to the interval between the two adjoining spiral turns, exerts a force C *d*, precisely equal, and in an opposite direction to C *e*. These two forces, therefore, exactly destroy one another; and there remains only the force C *f*, in the direction of the axis.

(107.) Experiment has fully confirmed the accuracy of this theoretical deduction: and the heliacal arrangement just described is found to be a tolerably exact representation of what may be conceived to be a simple or elementary magnetical filament; for it has opposite poles at the two ends, the one being north, the other south. It obeys the action of magnets that may be presented to it, being attracted and repelled, and assuming determinate positions with respect to the poles of the magnet, just as if it were itself a magnet, of which, indeed, it appears to possess all the essential properties, and for which it may be substituted in almost every form of experiment. It is hardly necessary to observe that the polarity of these *Voltaic magnets*, as we may call them, is entirely of a conditional nature, dependant on the passage of the electric current through them, ceasing the instant that current is arrested, and capable of being suddenly reversed by changing the direction of that current.

(108.) In order to facilitate the comparison of the properties of Voltaic magnets with those of ordinary magnets, it will be found convenient to adapt them to the simple floating galvanic apparatus devised by M. de la Rive. Such is the one represented in *fig.* 73.

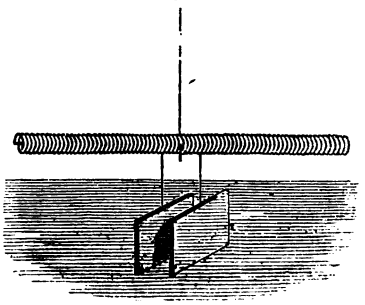
Fig. 73.



Both the ends of the wires are here made to descend through the cork, the one being soldered to the zinc, and the other to the copper plates; and the whole being enclosed in a glass cylinder adapted for floating it in water.

(109.) A very simple apparatus acting on the same principle, is that of Professor Vanden Boss, represented in *fig.* 74. It consists of a plate of copper about an inch square, and a similar plate of zinc, placed parallel to the former, their contact being prevented by a small piece of cork interposed between them. To the upper part of one of these plates a slender brass wire is at-

Fig. 74.

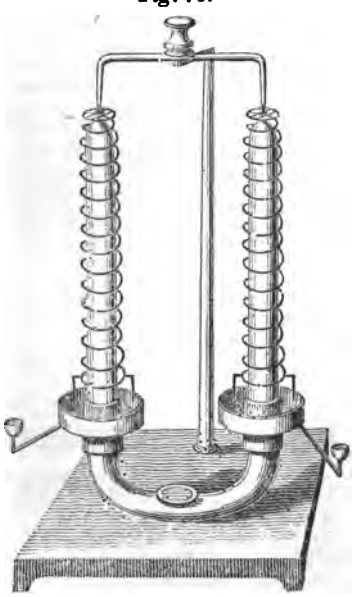


tached, which ascends, and is inserted into an opening made in the side of a long quill, or a tube formed of portions of quills inserted successively into each other, and about six or seven inches long. The wire, passing along the interior of the quills, comes out at the end, and being then wound round the outside of the tube in a helix, along its whole length, is made again to enter the quill at the other end; and proceeding back along the axis, is brought out near the middle, and made to descend till it meets the other plate, to which it is soldered. The whole apparatus is suspended at its centre of gravity by a piece of untwisted silk-thread. The plates being dipped into dilute acid, while thus supported, the galvanic action excited in them is sufficient to render the helix magnetical.

Heliacal Rotations.

(110.) An ingenious mode of exemplifying the rotatory action of a magnet on a conducting wire, when coiled into a helix, was contrived by Mr. Watkins, and described in his Popular Sketch of Electro-Magnetism*. The apparatus, represented in *fig.* 75, consists of a horseshoe magnet, firmly secured to a wooden stand. Each of the poles of the magnet

Fig. 75.



is encircled by a heliacal coil of copper wire, having a slender bar across its top, with a needle point in its centre, turning in a conical hole drilled in the end of the magnet, with a small platina cup above it, in order to hold a globule of mercury. The lower end of each of these coils terminates in slender, pointed wires, which are soldered to them, and which are intended to dip into mercury contained in a wooden cistern below it, fixed by screws to the leg of the magnet. A wire also proceeds from the lower part of each cistern, and, being bent upwards, terminates in a small cup, also capable of holding mercury. A brass standard rises from the basis of the apparatus, having a forked piece attached to its upper end, with two points descending into the two platina cups upon the tops of the coils; and there is also another cup placed at the top of the forked piece, holding mercury. The voltaic circuit may thus be completed in various ways; either by placing wires in the mercury contained in the small side cups, and connected with one pole of the battery, while other wires, communicating with the other pole, are placed in the cup on the top of the apparatus; or else, directing one and the same stream of electricity through the whole of the apparatus, by joining one of the side cups with the positive, and the other with the negative side of the battery. In the former case, the current, passing in the same direction, whether upwards or downwards, in the two coils, and being acted upon by the different poles of the magnet, will be urged to revolve in opposite directions: in the latter case, the contrary directions of the currents in both wires, ascending in the one, and descending in the other, being respectively acted upon in opposite modes by the contrary poles of the magnet, the combination of these two contrarieties will produce rotations in the same direction in both the wires.

Chapter VIII.

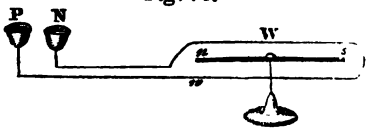
Galvanometers.

(111.) The action of a circular or spiral coil has been applied to the construction of an instrument for detecting small quantities of galvanic electricity, or *Galvanoscope;* and also of a *Galvanometer*, or instrument for measuring the intensity of any galvanic current. For this purpose, the diameter of the circle must exceed the length of the needle which it surrounds, in order to allow the latter to place itself in the plane of the circle

* P. 78.

which is to act upon it. Thus, if the needle *n s*, *fig.* 76, be placed in the same plane with the wire W *w*, proceeding from the two cups, P, N, and bent in a circular

Fig. 76.



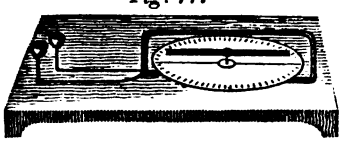
or oval form, so as to enclose it, the influence of every part of the wire when it so surrounds the needle, will be to turn both its poles in the same rotatory direction, until it takes a position at right angles to the plane of the figure. Let this plane be directed to the magnetic north and south—that is, coincide with the direction which the needle naturally assumes by the influence of the earth when left to itself, and undisturbed by the action of any electric influence; and let a feeble current of electricity be now sent through the wires: the effect of this current will be to occasion such a deviation of the needle from the plane of the magnetic meridian as will balance the force which the magnetism of the earth exerts in bringing it towards that plane. In proportion as the needle recedes from the meridian, the terrestrial force increases in intensity, while, at the same time, the electromagnetic force diminishes; the number of degrees at which it stops, and which mark where the equilibrium between these two forces takes place, will therefore indicate, with tolerable precision, the intensity of the galvanic current circulating through the wires.

(112.) The effect of a single turn, or coil of the wire may be increased by multiplying the coils; for in this way the same current is made to act repeatedly, in its course through the convolutions of the wire, upon the poles of the same needle. It is true that the electromagnetic force of the current is somewhat weakened by such an extension of the line of its course; but its diminution from this cause will scarcely be sensible, if the total length of the wire be not very considerable in comparison with the whole circuit of the current including the voltaic battery. In order to prevent the electric current from taking a shorter course than the one intended, it is necessary to secure the adjacent portions of the wires from coming in mutual contact; for such contact would allow of the direct passage of the current from the one to the other. For this purpose the wire must either be wrapped round with silk thread, or coated with sealing wax, throughout the whole length of the coil.

(113.) A galvanometer, constructed on this principle, was invented by Professor Schweigger, of Halle, very soon after the first discovery of Electro-Magnetism, and was called by him an *Electro-Magnetic Multiplier*. Various forms have been given to this instrument, either with a view to increase its sensibility, or to adapt it to different modes of application under particular circumstances.

(114.) One of the simplest forms of the instrument is that represented in *fig.* 77, in which a common compass-needle is suspended on a pivot proceeding from a wooden stand, and enclosed by a

Fig. 77.

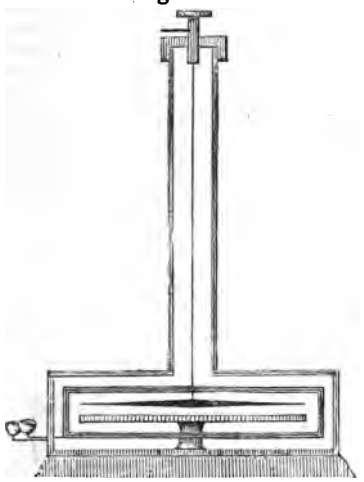


great number of turns of wire, bent into the shape of a vertical parallelogram, and the two ends of which terminate, as usual, in small metallic cups, containing mercury, for the purpose of establishing connexions with any galvanic combination of which we are desirous to ascertain and measure the electrical state. A graduated circle, having a dark line across it, coinciding with the plane of the wires, is to be fixed to the pivot, immediately under the needle, in order to estimate its deviations in either direction from that plane.

(115.) Greater mobility may be given to the needle by the more delicate mode of suspension employed in the balance of torsion. With this view, it may be suspended at its centre by a fine thread, or, what is best of all, by a single filament of silk, enclosed in a tube, and attached to the lower end of a short metallic wire, passed through the cover which closes the top of the tube, and capable of being turned in the aperture with some degree of friction, so as to bring the needle to any required horizontal position. The angular turning requisite for this purpose is marked by an index fixed upon the upper end of the

wire, by reference to a small graduated circle immediately below it, in the upper side of the cover. All these parts are represented in the vertical section, *fig.* 78. The other parts of the apparatus, as far as relates to the coils of wire which

Fig. 78.

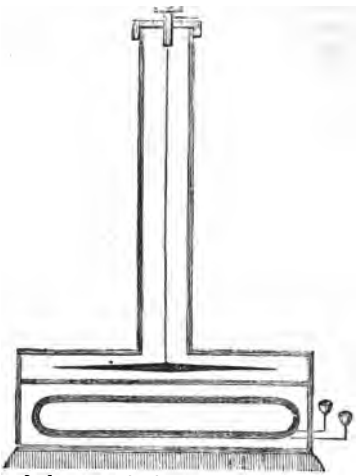


encircle the needle, are similar to those of the former instrument: excepting that the wires in the middle of the upper part of the coil must be separated a little, in order to leave an opening for the free passage of the thread that supports the needle. A graduated circle, equal in diameter to the length of the needle, is placed, as in the former case, immediately below the needle. The compass, wire, and card, are enclosed in a box, in order to secure them from the agitations of the air; and the cover, from the middle of which the upright tube rises, should be of glass, in order to allow of our seeing the position of the needle.

(116.) Mr. Ritchie has lately proposed a torsion galvanometer, in which he employs a thread of glass as the material for suspending the needle*. *Fig.* 79 is a vertical section of his instrument, of which he gives the following description:—Take a fine copper wire, and cover it with a thin coating of sealing-wax. Roll it about a heated cylinder, an inch or two in diameter, ten, twenty, or any number of times, according to the delicacy of the instrument required. Press together the opposite sides of the circular coil, till they become parallel,

* Philosophical Transactions for 1830, p. 218.

Fig. 79.



and about an inch, or an inch and a half long. Fix the coil in a proper sole, and connect the ends of the wires with two small metallic cups, for holding each a drop of mercury. Paste a circular slip of paper, divided into equal parts, horizontally on the upper half of the coil, and having a black line drawn through its centre, and in the same direction with the middle of the coil. Fix a small magnet, made of a common sewing-needle, or piece of steel wire, to the lower end of a fine glass thread, whilst the upper end is securely fixed with sealing-wax in the centre of a moveable index, as in the common torsion balance. The glass thread should be inclosed in a tube of glass, which fits into a disc of thick plate glass, covering the upper side of the wooden box, containing the coil and magnetic needle.

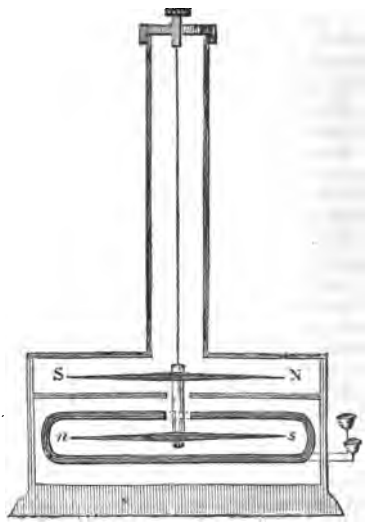
(117.) This instrument enables us to estimate the comparative intensities of currents of electricity circulating along the wires of the coil. For this purpose, the needle is to be placed directly above the meridian line drawn on the paper circle, and consequently directly above, and in the direction of the wires forming the upper side of the coil. As soon as a current of electricity is made to circulate along the wires, the needle will of course be deflected. The glass thread must then be twisted, by turning the index, until the needle is brought to its former position; and the number of degrees of torsion must be noted. A similar experiment may next be made with another current, the thread having

previously been untwisted, so that the needle is again restored to its former position. The quantities of electricity circulating round the wires will be directly proportional to the number of degrees through which the thread has been twisted.

(118.) In the common galvanometers, in which the force of the current is estimated by the degrees of the deviation of the needle, this deflecting force acts with mechanical disadvantage as the needle deviates from the coil. When it has been deflected nearly ninety degrees from its original position, an addition to the power will produce scarcely any addition to the effect; and consequently the instrument ceases to give indication of a more energetic current. Hence Mr. Ritchie's instrument is better entitled to the appellation of a *galvanometer*, or measurer of galvanic electricity, than the former, which are mere *galvanoscopes*, or indicators of the presence of a galvanic current. It has, however, the disadvantage of not being so sensible to the influence of feeble voltaic electricity; since the needle, being on the outside of the coil, is acted upon only by the difference of the two contrary electro-magnetic forces, arising from the opposite currents in the upper and lower parts of the coil. In the former arrangement, the needle, being between these two parts of the coil, is deflected by the sum of these forces.

(119.) The sensibility of the galvanoscope may be very much increased by neutralizing the directive force of the needle arising from the magnetic influence of the earth. Professor Cumming employed for that purpose a magnetized needle placed immediately beneath the moveable needle*. Nobili improved upon this idea by attaching the neutralizing needle to the principal one, placing them one above the other, and parallel to each other, but with their poles in opposite directions. They are fixed by being passed through a straw, suspended from a thread, as in the apparatus formerly described. The distance between the needles is such as to allow of the upper coil of the wires to pass between them, an opening being purposely left, by the separation of the wires at the middle of that coil, for allowing the middle of the straw to pass freely through it. A graduated circle, on which the deviation of the needle is measured, is placed over the wire on the upper surface of the frame of the instrument, having an aperture in its centre for the free passage of the needle and straw. The whole of this arrangement may be understood by a reference to *fig.* 80, which represents a section of the apparatus: *s n* is the lower needle

Fig. 80



surrounded by the coil of wire, and connected with the upper needle N S, by the intermediate straw shaft which is seen to pass through the upper horizontal coil of the wires, and also through the central aperture of the card immediately above it, on which the graduated circle is drawn. In Nobili's instrument, the frame was twenty-two lines long, twelve wide, and six high. The wire was of copper, covered with silk, one-fifth of a line in diameter, and from twenty-nine to thirty feet in length; making seventy-two revolutions round the frame. The needles were twenty-two lines long, three lines wide, a quarter of a line thick, and they were placed on the straw five lines apart from each other.

(120.) The adjustment of the opposing polarities of the two needles should be such, that the directive power of the combination resulting from the magnetism of the earth is very nearly balanced; the compound needle being allowed to retain only sufficient power to bring it to a constant position when uninfluenced by any electrical current. But the peculiar excellence of the contrivance.

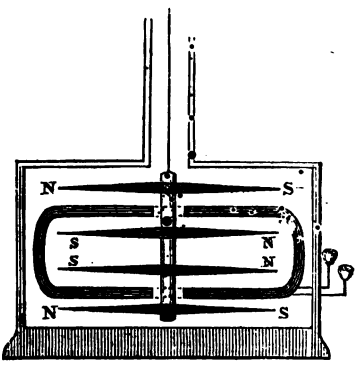
* Transactions of the Cambridge Philosophical Society, vol. i. p. 279.

is, that both needles are acted upon in the same manner, as far as the rotatory tendency is concerned, by the adjoining wires. The lower needle, being in the situation similar to that in the simple apparatus already described, § 91, is acted upon by the sum of the forces of the currents in every part of the coil. The upper needle, placed, with regard to the wires, in the same situation as in Mr. Ritchie's galvanometer, is acted upon by the excess of force in the upper current which is nearest to it. This force acts upon it in a direction the reverse of that in which it acts upon the lower needle, because it is situated on the opposite side; but since the poles are also in a reversed position, the rotatory action becomes the same in its direction on both needles. Hence, besides the increase of sensibility in consequence of the removal of the greater part of the opposing force derived from the magnetic influence of the earth, we have also an increase of power from the addition of the upper needle. There is also a convenience in employing the upper needle as an index; for by allowing of the graduated circle being placed above, instead of within the frame, the folds of the wire may be brought much nearer to each other than in the common instrument: this renders it more compact, and, from the greater approximation of the lower needles to the wires, also more powerful. The estimation of the deflection of the needle by reference to the graduated circle, can also be more conveniently made, from the view not being obstructed by the presence of the wires above the needle, as in the ordinary construction. It is hardly necessary to observe, that when fixing the graduation, the zero point should be placed so as to accord with the position of the upper needle, when left to the undisturbed action of the magnetism of the earth.

(121.) It is evident that if the magnetic powers of the two needles employed in Nobili's galvanometer were perfectly equal, they would exactly neutralize each other, as far as regards the directive influence of the earth; and the system of needles would be indifferent to any position. This would, however, defeat the purpose of the instrument, the object of which is to measure a feeble electro-magnetic force, by putting it in equilibrium with another force, likewise feeble, but still acting, and susceptible of measurement. If, therefore, a perfectly astatic needle, that is, one which retains no directive power whatever, be employed, it will be necessary to find some other weak, but variable and easily-measurable force to obtain this equilibrium. Such a force is that of torsion; and accordingly the greatest degree of perfection attainable in the measurement of minute electro-magnetic forces, would appear to be obtained by applying to the apparatus of Nobili, the needles being previously rendered perfectly astatic, the principle of the torsion suspension adopted by Mr. Ritchie.

(122.) An extension of the principle of Nobili's galvanometer has been proposed by M. Lebaillif; who employs a combination of four needles instead of two; one pair being applied to the upper part of the coil, and one pair to the lower, in the manner exhibited in the section, *fig.* 81, where N S, SN, represent the upper

Fig. 81.



pair of the magnets, having their poles in opposite directions; and S N, N S, the lower pair, likewise reversed in their polarities; the two intermediate magnets, which are within the coils of the wire, having their poles similarly situated, as is likewise the case with the uppermost, and lowermost magnets; and the whole being affixed to the same vertical axis, which is a piece of straw, passing freely through the wires, and through the graduated circle, which forms the top of the frame enclosing both wires and needles. An index is fixed in the upper end of the axis to point out the positions of the needles. The axis itself is suspended from the end of a horizontal arm, proceeding from an upright pillar at the side of the apparatus. In order to form the coil, M.

Lebaillif employs, instead of a single wire, having, for instance, a length of 300 feet, five parallel wires, each sixty feet long, the ends of which are stripped of their silk coverings and united in a bundle by being pressed together with considerable force. In this way the electric current which enters at one extremity is divided into five parts, and made to flow, as it were, through five separate channels. It is alleged, in favour of this arrangement, that by thus multiplying the channels of transmission, a proportionally larger quantity of electricity is conveyed; while the diminution of intensity arising from the transmission of the same fractional part of that current which passes through one of the wires, along a great length of wire, is avoided*. But experiments of sufficient extent, and conducted with sufficient care, appear to be wanting to enable us to deduce any certain conclusions with regard to this subject. The only researches on this point, of which we have been able to find an account, are those of Dr. Kaerntz, who came to the conclusion that the power of the instrument to deflect the needle is exactly in proportion to the number of convolutions of the wire: six convolutions giving six times the power of one convolution†. But it would require a much more extended investigation to establish such a principle, and to fix the limits of its operation.

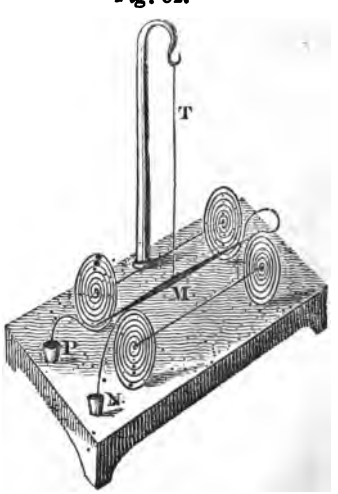
(123.) The advantage arising from the employment of four needles instead of two, in Mr. Lebaillif's instrument, appears extremely dubious; for it should be recollected that if, on the one hand, greater power is gained by the action of the wire on the additional needle, an equal addition is, on the other hand, made to the weight that is to be moved; so that probably nothing is thereby gained as to the motion indicating that power.

(124.) On account of the superior conducting power of silver, wires of that metal should be employed in preference to those of copper; and they may then be even as slender as the sixtieth of an inch in diameter, which will allow of a greater number of turns being included in the same space.

(125.) For the purpose of comparing the intensities of two electrical currents, an instrument has been contrived, which has been termed the *Differential Galvanometer*. Two wires of equal size are twisted together, so as to form a compound wire, which is coiled round the compass needle, as in the instruments already described; and the four extremities of the wires are immersed in four cups filled with mercury. By this means the two currents which are to be compared with one another, may be transmitted in opposite directions throughout the whole extent of the coil. These opposite currents, acting upon the needle under precisely similar circumstances, will, if they be equal, exactly counteract each other, and the needle will remain in equilibrio between the equal and contrary forces; but if the currents be unequal in intensity, the needle will be affected only by their difference, which it will therefore indicate by its movements.

(126.) When, on the contrary, we wish merely to ascertain the existence and direction of an electric current, it becomes an object to bring the current as near as possible to the needle, so that its action on the poles may be extremely powerful. The following form has, with this view, been given to the Galvanoscope. The needle is suspended from its centre by a fine thread, between four vertical spiral coils, the centres of which are brought very near to the poles of the

Fig. 82.



needle. The same current is made to circulate through all the four spirals, the turns of which are directed so as to produce repulsion of the contiguous pole

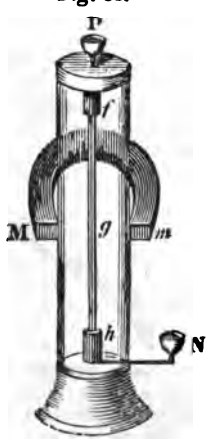
* See Pouillet's Elémens de Physique Expérimentale, tome i., p. 696.

† Philosophical Magazine, vol. lxii., p. 441.

on the one side, and attraction of the same pole on the other side. This arrangement is shewn in *fig.* 82, where M is the magnet suspended by the thread T, between the four spiral discs, composed of the convolutions of the wire proceeding from the cup P, and terminating in the cup N. In each disc, the force acting perpendicularly to the plane of the discs, is multiplied in proportion to the number of the circumvolutions of the wire; and the spiral turns being made in the same directions in all the discs, their actions will concur in producing in the needle a deviation in the same direction; and the total force will be four times that of a single disc. This arrangement allows also of a very close approximation of the needle to the discs.

(127.) The lightness and extreme flexibility of gold leaf have enabled electricians to employ this material for the construction of a very sensible electrometer. (See *Electricity*, § 73.) The same properties may be applied with great advantage to the purposes of a Galvanoscope, the electro-magnetic force of the current being estimated, not by the movements of a magnet on which it is made to act, but by those of a moveable conductor through which it is transmitted, under the influence of a powerful magnet. The construction of the *Gold-leaf Galvanoscope* is similar to that of Bennet's electrometer, excepting that the leaf is single, and there is added a forceps to retain the lower end of the gold-leaf, and complete the galvanic circuit. The slip of gold-leaf *g*, *fig.* 83, is suspended loosely from the forceps *f*,

Fig. 83.



while the lower end is laid hold of by another forceps *h*; each forceps terminating in a cup, the one, P, being above, and the other, N, below, for establishing the communications by which the current is transmitted through the gold-leaf. The whole is enclosed in a cylindrical glass case, the middle of which is placed between the poles of a strong horse-shoe magnet M *m*, so that the gold-leaf may be nearly equidistant from them. When the circuit is completed through the gold-leaf, the latter will be attracted or repelled laterally by the poles of the magnet, according as the current is ascending or descending; the broad surface of the leaf becoming convex towards the magnet in the one case, and concave in the other. The curvature of the gold-leaf may be viewed through a lens in a direction at right angles to the line of its motion, and may be referred to a fine line drawn upon the tube in the direction of its axis. This instrument is, perhaps, the most delicate test possible of the existence and direction of a weak galvanic current *.

Chapter IX.

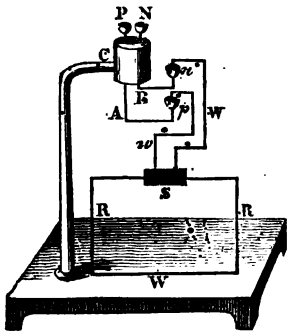
Electro-magnetic Effects of Terrestrial Magnetism.

(128.) Since the earth acts as if it were endowed with a magnetic power, or rather as if it contained a powerful magnet in its centre, it naturally occurred to those who explored the new realms of science which the discovery of Oersted had laid open, that a current of voltaic electricity would itself be influenced by the magnetism of the earth. It was at first found extremely difficult, however, to devise means of rendering this action visible, in consequence of the great feebleness of the earth's action, compared with that of such artificial magnets as we are in the habit of employing. Ampère at length succeeded in obtaining decisive evidence that the conducting wire possessed a directive power by the following contrivance. Two wires A and B, *fig.* 84, bent at right-angles, are made to pass through a cylindrical piece of wood C, fixed at the end of an arm proceeding from the basis of the apparatus. They are made to terminate at both their extremities in small cups, designed to hold mercury, the cups P and N being intended to receive the wires communi-

* Cumming's Manual of Electro-Dynamics, p. 178.

cating with the poles of the voltaic battery; and the others, *n* and *p*, which are placed the one immediately above the

Fig. 84.



other, receiving the two ends of the wire W W *w*, which passes through a small piece of wood at S and is bent below into a square or rectangle R R. The upper point of the wire rests on the bottom of the cup *n*; the lower point being merely made to dip into the mercury in the cup *p*, without touching it, so that the whole of the wire, with its connecting piece S, has perfect freedom of motion round a vertical axis passing through the point of support in the uppermost of the two cups, *n*. When a connexion is made with the battery by means of the cups P and N, so as to direct an electric current through the wire W W *w*, it will, from the extreme delicacy of its mode of suspension, obey the magnetic influence of the earth, and arrange itself so that the plane of the rectangle R R shall be perpendicular to the plane of the magnetic meridian; and it will always return to this position when turned aside from it by the hand, or any other cause.

(129.) Another arrangement which exhibits the same effect is the one already described, § 100, and represented in *fig.* 66; where the electro-magnetic force is increased by the number of coils composing the spiral wire. This spiral, as in the last case, immediately assumes a position in a plane perpendicular to the magnetic meridian, as soon as it is made the channel for the transmission of a current of voltaic electricity. The mode of suspension here described is that of Professor Van den Boss*.

(130.) The apparatus invented by M. De la Rive, and described § 96, with the improvement described in § 99, is also exceedingly well adapted for the exhibition of the directive power of the galvanic current; for in consequence of the perfect freedom of motion allowed it, while floating in a fluid, it very readily assumes the position due to the magnetic influence of the earth. When the plates are immersed in acidulated water, as in M. De la Rive's original experiment, the gas liberated by the action of the acid on the plates, prevents them from taking a steady position; but when put into a little floating cell, the whole readily takes the position above mentioned, and even slowly vibrates about it. The same phenomenon is also obtained by the arrangements described in § 108 and § 109, which have also the advantage of exhibiting the strong resemblance which these instruments, actuated solely by electrical currents resulting from galvanic action, have to artificial magnets. For in consequence of their lengthened cylindrical form, the magnetic forces are directed along the axes, and the heliacal cylinder places itself, like a magnet, with its axis in the magnetic meridian; whereas, when a single circle, or combination of circles in a single plane is taken, that plane will arrange itself so as to be at right angles to the plane of the meridian, that is, will be in a plane passing east and west; the face of the plane only looking to the north and south.

(131.) In all the cases above described, the multiplication of the spiral or circular turns of wire is not productive of the advantage that might be expected, because, as already remarked with regard to the galvanometer of Lebaillif, § 123, although the power is increased, yet the weight to be moved by that power is increased nearly in the same proportion; and the resulting motion is therefore nearly the same.

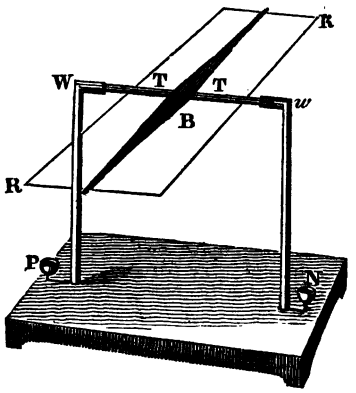
(132.) The next point of comparison between the action of the earth on the conducting wire, and on the magnetized needle, relates to the dip. Since the direction of the force of terrestrial magnetism is in a line situated in the magnetic meridian, and inclined about seventy degrees to the horizon, the operation of this force on a Voltaic wire, bent in a plane so as to describe a circle, square, parallelogram, or any other figure which terminates where it commenced, forming what has been termed a *closed circuit*, is to bring it into a position where it is perpendicular

* Edinburgh Journal of Science, No. XII.

to this direction; that is, perpendicular to the position of the dipping needle.

(133.) The following was the apparatus, by which Ampère succeeded in exhibiting the effect now described. A

Fig. 85.



wire bent in the shape of a rectangle R R, *fig.* 85, is supported by a tube of wood, T T, passing directly across the middle of its longest sides, and serving as an axis. The two shorter sides or ends of the rectangle are supported by a light wooden beam, B, in the form of a lozenge, the middle of which is perforated by the tube just mentioned. One end of the wire, W, which forms the rectangle, is fixed to a steel pivot, which turns horizontally on a small metallic plate fixed upon the top of an upright metallic pillar, rising from the side of the basis of the apparatus. A little mercury is laid upon the plate in order to render the contact more perfect. The wire, after it has completed a circuit of the rectangle, and returned to the same point W, where it had commenced it, is bent so as to pass through the tube, and to come out at the other end, *w*, where it terminates in another steel point, turning in a like manner upon a metallic plate, fixed on the top of a pillar on the other side of the apparatus. The lower ends of both pillars, where they are fixed to the stand, are continuous with wires supporting cups with mercury, P and N, in the usual manner. On establishing a communication between the Voltaic battery and the cups, the electric current will ascend in the pillar which is next to the positive pole of the battery, and circulating along the rectangular wire, will pass out by its other extremity, descend by the other pillar, and make its exit through the cup on that side. As the rectangle is at perfect liberty to move around the axis formed by the two points by which it rests on the plates, and this axis being horizontal, it will be limited to a vertical motion. If the axis of motion be placed so as to be at right angles to the magnetic meridian, and the moveable part of the apparatus be exactly balanced, so as to retain any position in which it may be placed, then on directing the electric current through the wires, the rectangle will, after a few oscillations, place itself steadily in the plane of the magnetic equator; that is, in a plane perpendicular to the line of the dip; being the exact position which the theory would assign to it. On reversing the direction of the current, the magnetic polarity of the wire becomes immediately reversed, and turns completely round, so as still to place itself in the same plane as before, but with its faces turned in opposite directions to those they before assumed.

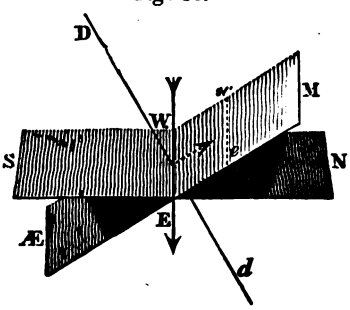
(134.) It is evident that, by adopting a similar mode of suspension, a voltaic magnet, formed by a heliacal coil of wire, as described in § 105, would exhibit the phenomena of the dipping needle, as completely as a magnetized needle.

(135.) Thus has the analogy between the action of terrestrial magnetism on wires conducting an electric current, and magnetized needles, been completely established. We have next to inquire whether a straight wire is affected by the earth in the same manner as it would be by the corresponding pole of a magnet placed near it. In order to make this comparison, we must first clearly deduce from the theory formerly laid down, what effects are to be expected on a straight conducting wire from the magnetism of the earth, or what is equivalent to it, from a south magnetic pole, acting at an indefinite distance, in the direction of the line of the dip. The electro-magnetic force being tangential, is exerted at right angles to this direction, which is that of the line connecting the wire with the magnetic pole, or origin of the force. Its action upon a current, whether ascending or descending, which moves in this exact line, or the line of the dip, is reduced to nothing: and it must act with greatest intensity upon a current which moves in a direction perpendicular to the line of the dip. Now, in order that a straight wire may be

perpendicular to this line, it must be situated in the plane of the magnetic equator. Such, then, is the direction in which it receives the full influence of the earth's magnetism; and this influence is exerted in urging it to move in a direction parallel to itself, and at the same time perpendicular to the line of the dip; that is, it tends to continue in the plane of the magnetic equator. The direction of its motion to the one side or the other must depend altogether upon the course of the electric current which is passing through it. If the wire, for example, be placed horizontally, and have the direction of the magnetic east and west, and the current of positive electricity be flowing through it from west to east, the tendency to motion in the wire, in consequence of the influence of the earth, which acts like a south pole, is towards the *north*, that is *ascending* in the plane of the magnetic equator, which plane, it may be recollected, dips downwards towards the south, with an inclination to the horizon of about twenty degrees, equal to the complement of the dip.

This will be more clearly understood by reference to *fig.* 86, in which N, E, S, W represents a horizontal plane. D *d*, which has an inclination to this plane of 70°, is the line of dip, to which the plane M Æ, representing the plane of the magnetic equator, is perpendicular. W E is a straight portion of conducting wire, along which an

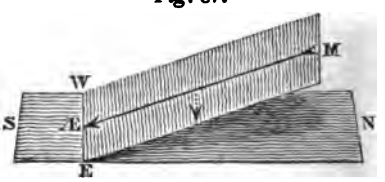
Fig. 86.



electric current is flowing in the direction from W to E. Under these circumstances, the effect of the electro-magnetic force exerted by the earth is to give the wire a tendency to move parallel to itself, in the plane M Æ, and towards M, as denoted by the arrow; so that were it at liberty to obey this impulse, it would next be found to occupy the position marked by the dotted line *w e*. If the electric current had been made to pass from E to W, the direction of the motion would have been altered, and the wire would have moved downwards in the same plane, still, however, preserving its parallelism.

(136.) If the wire extend in the magnetic plane from north to south, as, for instance, along the line M Æ in *fig.* 87, N S, as before, being the horizontal plane: and if the electric current move in the direction M Æ, that is,

Fig. 87.



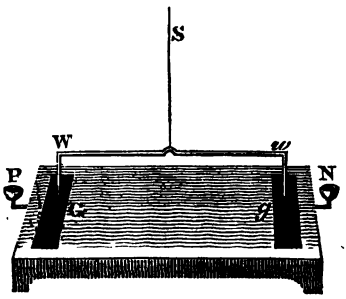
from north to south, the wire will tend to move towards the east, as shewn by the arrow, still keeping in the same plane, and remaining parallel to itself. If, on the contrary, the current move from south to north, the wire will be impelled to move from east to west.

It need hardly be observed that all these statements relate to what happens in the northern magnetic hemisphere of the earth, and when the dip is about 70 degrees, as is the case in England. In the southern hemisphere, where the northern polarity of the earth is in activity, the effects are of course reversed. At the magnetic equator, where the dip is nothing, the plane M Æ is perpendicular to the horizon, and the tendency to motion of a horizontal wire must be directly upwards, or directly downwards; and the effect of the terrestrial magnetism must be merely that of opposing or conspiring with gravitation, that is of producing either an increase or a diminution in the apparent weight of the wire. In these high latitudes the inclination of the magnetic equator to the horizon is too small to produce any very sensible effect of this kind. It has, however, been rendered perceptible in very nice experiments

(137.) In consequence of the plane of the magnetic equator being not very far removed from a horizontal plane, wires placed horizontally, and being free to move in a horizontal plane, may be made to exhibit the actions of terrestrial magnetism without much difficulty. Mr.

Faraday succeeded in obtaining this effect in the following manner*. A piece of copper wire, about .045 of an inch thick, and fourteen inches long, has an inch at each extremity bent at right angles in the same direction, as shown at W *w*, in *fig.* 88, and the ends amalgamated; the wire is then to be sus-

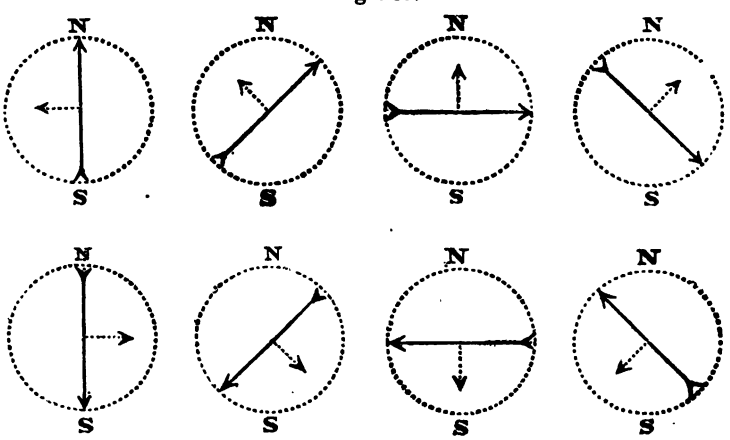
Fig. 88.



pended horizontally, by a long silk thread *s*, from the ceiling. Two grooves G *g* are cut in the sides of a rectangular piece of hard wood, parallel to the sides, and about half an inch in depth, and filled with mercury. P and N are wires fixed in the board, passing each into its respective groove, so as to come in contact with the mercury, and terminating at their other ends in cups for making the connexions with the voltaic battery. The points of the wires are now to be slightly immersed in the mercury contained in the respective grooves; and in order to obviate the inconvenience arising from the film of oxide which is apt to form upon the surface of the mercury, and impede the motion of the wires, it is advisable to cover the surface with a stratum of diluted nitric acid, which, by dissolving the oxide, removes this obstacle to free motion. As soon as the connexions are made with the battery, and the electric current passes along the wire, it will be seen to move laterally, being carried across the field until the points strike against the ends of the grooves. On breaking the connexion, the wire resumes its first position; on restoring it, motion is again produced. On changing the position of the apparatus with respect to the points of the compass, the same effect still takes place; and the direction of the motion is always the same relatively to the wire, or rather to the current passing through it, being at right angles to it. Thus, when the wire is east and west, and the electric current flowing from west to east, the motion is towards the north; when the current passes from east to west, the motion is towards the south. When the wire hangs north and south, and the current moves from north to south, the wire is directed towards the east, and when the current is reversed, towards the west. In intermediate positions the motions of the wire are in intermediate directions.

(138.) These different motions corresponding to the different positions of the wire, and directions of the current, are exhibited by the lines in *figs.* 89, in which N and S express the north and

Figs. 89.



* Quarterly Journal of Science, &c., Vol. XII. p. 417.

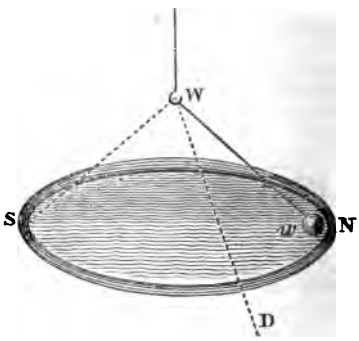
south; the arrow-heads at the end of the lines shew the direction of the current in the wire; and the short arrows proceeding laterally from the middle, the direction of the motion induced in the wire.

(139.) It is evident that, in all these cases, the wire is moving in obedience to the same law, which produces the revolution of a wire round a magnetic pole in Mr. Faraday's first experiment on magnetic rotations, already described (§ 59). It is a direct and necessary inference from this law, that were the two troughs of mercury continued to ever so great a length, and even were they carried round the globe in a circle round the acting magnetic pole of the earth, the wire would continue to move along them, and after describing the whole circle, and returning from the point at which it had set out, would resume its course, and perform perpetual revolutions. In the very limited space compatible with actual experiment, the wire appears to move in a plane; but theory shews that it is in reality a small portion of a cylinder, of which the radius is the distance of the magnetic pole of the earth from the wire. It is amusing to compare this incipient revolution of the wire with the complete rotations effected in experiments with artificial magnets; and, considering it as part of a similar experiment upon a much vaster scale, to view the wire as setting out on its voyage of circumnavigation of the globe, although it is in the next moment arrested in its progress.

(140.) It is also a consequence deducible from the same law, that the force by which the horizontal conducting wire is urged is the same in all azimuths.

(141.) A real rotation, visible in all its course, may however be exhibited, as the effect of terrestrial magnetism. This has been accomplished also by Mr. Faraday, who, reflecting that in the experiment of rotation round the pole of a magnet, the pole is perpendicular to but a small portion of the wire, and more or less oblique to the rest, thought it probable that a wire, very delicately hung and connected, might be made to rotate round the line of dip by the earth's magnetism alone; the upper part being restrained to a point, in the line of the dip, and the lower being made to move in a circle surrounding it. With this view, a piece of copper wire, about 0.018 of an inch in diameter, and six inches long, well amalgamated all over, was hung by a loop to another piece of the same wire, at W, see *fig.* 90, so as to allow of very free motion; and its lower end *w*, was thrust through a small piece of

Fig. 90.

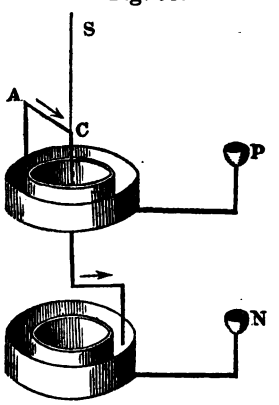


cork, in order to render it buoyant when placed on mercury. A glass basin, ten inches in diameter, was filled with pure clean mercury, and a little dilute acid poured on its surface. The thick wire which communicated with one of the poles of the voltaic battery was then hung over the centre of the glass basin, and depressed so low, that the thin moveable wire, having its lower end resting on the surface of the mercury, made an angle of about 40 degrees with the horizon. On the circuit through the mercury being completed, the wire immediately began to move and rotate, and continued, whilst the connexions were preserved, to describe a cone, which though its axis was perpendicular, had, evidently, from the varying rapidity of its motion, relation to a line W D, parallel to the dipping-needle, as being that of the force by which it was actuated. The direction of the motion was, of course, the same as that communicated in the experiment described § 64, when a south pole is placed beneath the apparatus. If the centre from which the wire hung was elevated, until the inclination of the wire was equal to that of the dip, no motion took place when the wire was parallel to the dip; and if the wire was less inclined than the dip, the motion in one part of the circle capable of being described by the lower end was reversed; results that necessarily follow from the

relation between the dip and the moving wire*.

(142.) It is evident that by restraining the motion of one of the ends of the horizontal wire in the experiment described in § 137, and represented in *fig.* 88, so as to render that end a fixed axis, and providing a circular mercurial trough for the other end to move in, the same force which produced a parallel progressive motion in the former case, will now produce a rotatory motion; because the force producing a horizontal motion is the same in all positions of the wire. This equality is proved by making the experiment with two connected horizontal wires instead of one; placing them the one immediately above the other, each being furnished with its separate mercurial trough, into which the moveable end may dip. This arrangement is represented in *fig.* 91, where the current entering by the cup P, and traversing the mercury in the upper trough, ascends through the wire A, passes on through the upper horizontal wire to the central wire C, placed in the

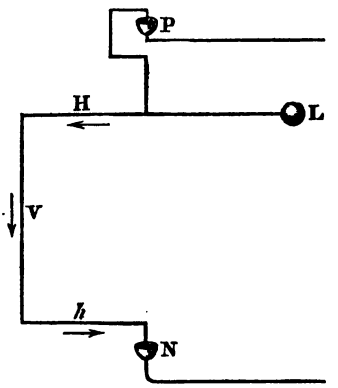
Fig. 91.



axis of suspension, (the wire being hung by the slender thread S,) along which it descends, and passes *outwardly* through the lower horizontal wire, and thence through the mercury in the lower trough, to the cup N, whence it escapes to the voltaic battery. When this has been effected, it is found that the suspended wires exhibit no tendency to rotate, in whatever azimuth they may be placed. Hence it may be inferred that the tendency to revolution which the earth communicates to the current moving from the circumference to the centre in the upper horizontal wire, is exactly counterbalanced by an opposite rotatory force in the lower wire, in which the current passes from the centre to the circumference; and as this equality is preserved in every azimuth, it follows that the rotatory force is constant in every position of the wire.

(143.) A vertical current in a conductor moveable round a vertical axis is also impressed by the influence of the earth with a horizontal force, which carries it towards the magnetic east, when the current is descending, and towards the west when it is ascending. This will be made apparent by suspending a wire bent as shown in *fig.* 92, A, and terminating above and below in the points P and N, for the purpose of being placed in their respective cups, and

Fig. 92, A.



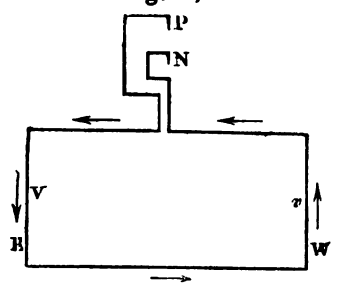
balanced by a counterpoise, L. When the current is passed through this wire, the direction of its course along the two horizontal branches, H and *h*, being opposite, will counterbalance each other; but that in the vertical portion, V, will take a position either to the east or west of the axis, according as the current descends or ascends through it.

(144.) If the wire, instead of having the shape just shown, has the figure of a complete square or parallelogram, as shown in *fig.* 92, B, the second vertical branch will conspire with the first in making the wire assume the same position, namely, that in which the current descends, (as V,) to the east, and that in which it ascends, (*v*,) to the west.

(145.) From an attentive consideration of the facts that have now been stated, we are enabled to understand why a vertical circular current, urged by the

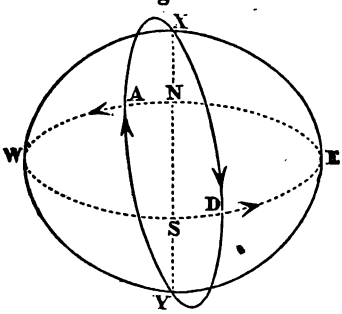
* Quarterly Journal of Science, XII. 418

Fig. 92.



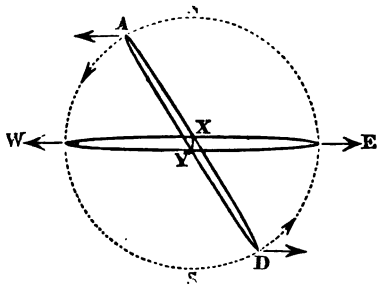
electro-magnetic force of the earth, tends to arrange itself in the plane of the magnetic equator. If at liberty to do so, it will assume this position; but if its motion be restricted to any other directions, it will place itself as nearly as possible in that plane. If, for instance, it be constrained by a vertical axis to turn horizontally only, it will place itself in a plane perpendicular to that of the magnetic meridian; that is, directed east and west, or fronting to the north and south. In its movements to attain this position, it is urged by the tendencies of the currents, in as far as their motion is vertical, whether ascending or descending; for the tendencies of the horizontal portions exactly balance one another, and produce no rotatory effect. Thus if in the circle A D, *fig.* 93, which turns on the vertical axis, X Y, the current descend in the branch D, and ascend in the branch A, the former

Fig. 93.



will be impelled in the direction D E, and the latter in the direction A W, by forces which cease only when they have attained the positions E and W. The horizontal portions at X and Y neutralize each other, with regard to their rotatory tendency. Hence the circle will revolve until it takes the position shown by the circle at E and W, where the forces are in equilibrium. The nature of this equilibrium will appear from *fig.* 94, in which the circle is represented as seen from above; and the arrows point out the horizontal direction of the forces, which when the circle is in the line W E pass through the vertical axis and are exactly balanced. The same letters denote the corresponding points in the two figures.

Fig. 94.



(146.) When, on the other hand, the axis of revolution is horizontal, and the motion vertical, the position is determined by the forces that act on the horizontal parts of the circle, which now conspire in determining a rotation towards the plane of the magnetic equator, if the plane of motion coincide with the magnetic meridian; or if not, as near to it as the restrictions to the motion will allow.

(147.) On the whole, then, it appears that a heliacal coil, such as that described in § 105, balanced on its centre, will assume all the positions, and exhibit all the directive properties of the magnetic needle.

Chapter X.

Electro-Magnetic Induction.

(148.) Thus far we have considered the electro-magnetic phenomena that result from the reciprocal action of galvanic currents on magnetized bodies. We have next to examine that class of effects which arise from the action of the former on iron, or other ferruginous bodies that have not previously been rendered magnetic. Experiment has proved that a conducting wire, during the passage of an electric current through it, tends to induce magnetism in such bodies as are in the vicinity, and in which that state is capable of being

excited. *Induction*, therefore, is one of the phenomena of electro-magnetism, and must be enumerated among the properties of electricity in motion.

(149.) It was discovered both by Sir Humphry Davy and by Mr. Arago, nearly at the same time, that the connecting wire of a galvanic battery has a sensible attraction for iron filings, and that it will hold them suspended like an artificial magnet, as long as the electric current circulates through the wire; but the moment the galvanic circuit is interrupted, the action ceases, and the filings immediately fall off. In Sir H. Davy's experiments, the filings adhered to the wire connecting the poles of a voltaic apparatus, consisting of a hundred pairs of plates of four inches, in such considerable quantities as to form a mass round it ten or twelve times the thickness of the wire*.

The transverse magnetic action of the electric current upon iron in its vicinity is beautifully illustrated by the following experiments, which were devised by Mr. Watkins, and which he was so obliging as to show us. A copper wire of considerable thickness is extended between the poles of a voltaic battery; and upon sifting over it very gently some fine iron filings, they are observed to adhere to the wire all round its circumference, in the form of distinct transverse bands, the particles of which mutually cohere, as long as the current is maintained. When a broad and thin copper ribbon is substituted for the wire as the conductor of the voltaic electricity, and iron filings are carefully sifted upon it in small quantities, they are seen to arrange themselves in parallel lines at right angles to the length of the ribbon; and their magnetic properties are further evinced by the quick changes of position and general disturbance occasioned by the approach of a magnet brought underneath the conducting plate.

(150.) It might naturally be expected from these experiments with soft iron, that steel, under the same circumstances, would receive a permanent magnetism. Sir Humphry Davy, having fastened several steel needles, in different directions, by fine silver wire, to a wire of the same metal, of about the thirtieth of an inch in thickness, and eleven inches long, some parallel, others transverse, above and below, in different directions, placed them in the electrical circuit of a battery of thirty pairs of plates of nine inches by five, and tried their magnetism by means of iron filings. They were all magnetic; those that were parallel to the wire attracted filings in the same way as the wire itself; but those in transverse directions exhibited each two poles. All the needles that were placed under the wire when the positive end of the battery was east, had their north poles on the south side of the wire, and their south poles on the north side; while those that were over the wire had their south poles to the south, and their north poles to the north; and this was the case whatever was the inclination of the needles to the horizon. On breaking the connexion, all the steel needles that were on the wire in a transverse direction retained their magnetism, which was as powerful as ever, whilst those that were parallel to the silver wire appeared to lose it at the same time as the wire itself.

(151.) All the needles placed transversely *under* the communicating wire, the positive end being on the right hand, had their north poles turned towards the face of the operator; and those *above* the wire, their south poles. Contact with the wires was not at all necessary for the magnetization of the needles; for this effect is produced instantaneously, by the mere juxtaposition of the needle in a transverse direction, and that through very thick plates of glass. A needle that had been placed merely for an instant in this transverse direction with regard to the wire, was rendered as powerful a magnet as one that had long been in communication with it.

(152.) The intensity of the induced magnetism was found to be proportional to the quantity of electricity transmitted through the wire in a given time. Hence a wire electrified by a common machine, however powerful, produces no sensible effect; a feeble magnetism only is obtained by the reception of large sparks: but on passing the discharge from a Leyden battery through the wire, the needles placed transversely to the wire are rendered permanently magnetic. The discharge of an electrical battery of seventeen square feet, highly charged, through a silver wire of the twentieth of an inch in thickness, rendered bars of steel two inches long and from one-twentieth to one-tenth of an inch in thickness, so magnetic, as to enable them to attract small pieces of

* Philosophical Transactions for 1821, p. 9.

steel wire or needles; and the effect was communicated to a distance of five inches above or below laterally from the wire, through water, or thick plates of glass or metal electrically insulated.

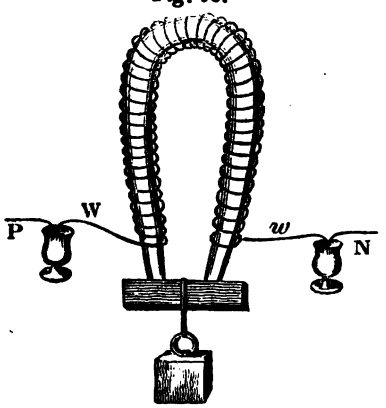
(153.) The efficacy of electro-magnetic induction is, as might be expected, greatly increased by employing a heliacal coil of wire, and placing the needle or bar to be magnetized in the axis of the helix, in the situation represented in *fig.* 67. Mr. Arago first employed this method, and was enabled to produce the maximum effect on the needle almost instantaneously. It is not necessary, however, that the bar to be magnetized should be exactly in the axis of the helix, as it may lie in any situation within it, or be inclosed in a tube of glass, or of any other material which is not a good conductor of electricity. Such a tube will also be convenient as a support for the coils of the wire, as well as for admitting of the introduction of different needles in succession. The needle should not be allowed to remain beyond a moment in the tube, for the magnetizing effects of the helix are produced nearly instantaneously; and it sometimes happens that if the needle be left there a few minutes, the polarity it had at first acquired becomes impaired, or confused, and even occasionally destroyed.

(154.) If a long steel wire be placed in the axis of a helix, the direction of the turns of which change at different points, the wire will be found to have a number of consecutive points, corresponding to those at which these changes take place.

(155.) Mr. Watkins observes that the needle to be magnetized, if it be not very hard, need not have its whole length inserted into the glass tube; for if held in the hand so that only half of it is within the helix, it will become magnetic equally with one that has been wholly acted upon; because the portion of the needle that has received the magnetism communicates it to the other portion. When a small part of a needle, very highly tempered, is introduced into the glass tube, the induced magnetism will be found to extend to about twice the length of the part so introduced.

(156.) A very powerful temporary magnet may be obtained by bending a thick cylinder of soft iron into the form of a horse-shoe, and surrounding it with a coil of thick copper wire, secured from communication among its several parts by a covering of silk, or other non-conducting material. When the wire is made part of the galvanic circuit of a battery, even of moderate power, the iron is rendered powerfully magnetic, and will lift up a very heavy weight by means of a piece of iron applied to its poles, which act precisely like those of a horse-shoe magnet. *Fig.* 95 exhibits an arrangement of this kind; W *w* being the two ends of the wire, coiled round the iron to be magnetized, and bent so as to dip into the cups P and N, for forming connexions with a battery.

Fig. 95.



(157.) This experiment has been made upon a very large scale by Professor Moll with an apparatus constructed by Mr. Watkins*. It consisted of a cylinder of soft English iron, an inch in diameter, bent into the form of a horse-shoe, the interval between the ends being eight inches and a half. The copper wire forming the spiral was one-eighth of an inch in diameter, and made eighty-three convolutions; the weight of the whole was five pounds. A connecting piece of iron was placed in contact with the two extremities of the horse-shoe; and the ends of the spiral wire dipped in mercury, so as to form a voltaic circuit with a simple battery, consisting of a zinc plate, which exposed a surface of eleven square feet to a very diluted mixture of sulphuric and nitric acids, in a copper cell. In the first experiment the apparatus sustained, first, fifty pounds, and afterwards, with care, seventy-six pounds, by the magnetism induced upon it.

(158.) When the weight suspended to

* Bibliotheque Universelle, 1830, p. 12.

the transverse bar of iron is small, it is found that the iron retains its magnetism for some time after the voltaic communication is broken. If, instead of merely breaking the connexion, the electric poles are changed so as to reverse the direction of the current, then the reversion of the magnetism takes place with extraordinary rapidity. The weight, indeed, falls off, but is instantly again attracted and sustained with the same force as before. The rapidity of this change is the more extraordinary when it is compared with the slowness and difficulty of changing the poles of a magnet of equal force by the ordinary method. If, instead of a heavy weight, a light steel needle be in contact with the poles of the electro-magnet, the needle never falls off; the attractive force being destroyed and re-established before the weight of the needle has time to effect its removal.

(159.) An extraordinary sensation is experienced when the piece of soft iron connecting the poles is held in the hand during this change. At first a powerful attraction is felt; this on a sudden fails, and the iron gives way; but the force is so instantaneously renewed, that the hand is violently drawn up again by an attraction as strong as before. The moment the voltaic circuit is completed, the iron is magnetized to a maximum, and sustains its greatest weight. No increase of magnetic power is obained by augmenting the force of the voltaic battery.

(160.) With a larger horse-shoe magnet of soft iron, weighing twenty-six pounds, and of which the diameter was two inches and a half, the chord of the arc being twelve inches and a half, and the spiral wire being of brass, one-eighth of an inch in diameter, and making forty-four turns, and with the same voltaic battery as in the former experiment, the magnet supported 139 pounds. When an iron wire was used, instead of a brass one, this was increased to 154 pounds.

(161.) However great these effects may appear, they are much increased by augmenting the number of coils, without extending the length of the wire. Professor Henry, of the Albany Academy, in the United States, and Dr. Ten Eyck, employed for the construction of the magnet a soft iron bar, two inches square, and twenty inches long, having the edges rounded, bent into the form of a horse-shoe. Five hundred and forty feet of copper bell-wire was wound round it, in nine coils of sixty feet each. These coils were not continued from one end of the magnet to the other, but each of them was wound round a portion of the horse-shoe about an inch in length, leaving the ends of the wires projecting, and properly numbered. The alternate ends were soldered to a copper cylinder, and the others to a smaller cylinder of zinc, containing only two-fifths of a square foot, and forming a voltaic arrangement with dilute acid. When the armature of soft iron was placed across the ends of the horse-shoe, it was found capable of supporting 650 pounds; an astonishing effect for so small a battery, which required a charge of only half a pint of dilute acid. With a larger battery, the weight sustained was 750 pounds, which seemed to be the maximum of magnetic power that could be developed in that bar by voltaic electricity. It is remarkable that when the ends of the wires were united so as to form a continuous wire of 540 feet, the weight raised was only 145 pounds.

In a subsequent experiment, a magnet was wound with twenty-six strands of copper bell-wire, covered with cotton thread, thirty-one feet long; about eighteen inches of the ends were left projecting, so that only twenty-eight feet of each actually surrounded the iron. The aggregate length of the coil was, therefore, 728 feet. Each strand was wound on a little less than an inch; in the middle of the horse-shoe it formed three thicknesses of wire; and on the ends, or near the poles, it was wound so as to form six thicknesses. With a battery nearly five feet square, this electro-magnet suspended 2063 pounds, or nearly a ton weight. This appears to be the most powerful single magnet ever constructed, either by the ordinary modes of magnetizing steel bars, or by the voltaic current.

(162.) Trials were also made to procure a small temporary magnet, which should raise the greatest weight, compared with its own weight. A small horse-shoe of round iron, slightly flattened, one inch in length, and six tenths of an inch in diameter, wound round with three feet of brass wire, raised, by means of a cylindrical battery, 420 times its own weight. Sir Isaac Newton describes a magnet weighing

three grains, which he wore in a ring, and which is said to have raised 746 grains, or 250 times its own weight, and this is the greatest relative strength of any magnet yet recorded. It is evident, therefore, that a much greater degree of magnetism can be developed in soft iron, by a galvanic current, than in steel of the same dimensions, by the ordinary processes of magnetizing*.

Mr. Watkins informs us that, in order to obtain magnets of any power by the above described method, great care must be taken to ensure the purity of the iron employed to form the horse-shoe magnet; and after it has been welded and reduced to the proper shape, it is advisable, in order thoroughly to destroy any magnetism it may have accidentally acquired and retained during the process, to heat it in a furnace, and afterwards cool it very gradually, by allowing it to remain undisturbed till the furnace itself has grown cold. But, even after every precaution has been taken to ensure success, we are still liable to be baffled by causes which we cannot explain, and which, when all circumstances seem to be the same, produce great and unexpected variations in the results. It should be borne in mind, indeed, that similar embarrassments are often experienced in conducting almost every other experiment in electro-magnetism, their results appearing to be more or less capricious in proportion as the conditions necessary to be fulfilled, before uniformity can be obtained, are numerous and delicate.

(163.) The best form of a conducting-wire for exhibiting its attraction for iron filings is that of a flat spiral coil, similar to what is represented in *fig.* 66, which, however, for this purpose need not be rendered moveable. A wire of this form, through which an electric current is made to circulate, will collect a prodigious quantity of iron filings, and their relative positions and arrangement, while they remain attached, present many singular appearances. If the rings of wire are not continued quite to the centre, but leave an opening there, the particles of iron are observed to arrange themselves in lines, passing through the ring parallel to the axis, and then closing up as radii round the edge. The particles of iron in the centre erect themselves into a perpendicular filament, in the direction of the axis of the spiral, while the intervening particles form filaments inclining from the centre in proportion to their distance from it*. The reason of this will be evident from the principle explained in § 50.

(164.) There appears to be a very essential difference in the effects of the shock of an electrical battery discharged through a wire, and that of a voltaic battery, in communicating permanent magnetism to steel bars or needles. Mr. Savary has brought to light several very curious particulars relating to this subject, which have hitherto received no explanation†. When the discharge from a Leyden battery is made through a straight wire, different needles, though equal in size, and parallel to each other, and placed transversely on the same side of the wire, but at different distances, have their polarities not disposed in all of them in the same manner. In some the poles have the same relative situation as those of a needle previously magnetized, and free to move, which has taken the position it would have when under the influence of a continued voltaic current passing in the same direction along the wire.

But in others the position of the induced poles is the reverse of this. For the sake of conciseness of expression, we shall call the action which produces an arrangement of poles similar to that resulting from a voltaic current, *positive magnetization*; the contrary effect being that of *negative magnetization*. Thus, in a series of experiments in which the needles were placed at distances from the wire which increased by equal intervals, at the point of contact with the wire the needle was magnetized positively, at a small distance negatively; a little further off it had acquired no magnetism whatever; at a distance somewhat greater than this, it exhibited positive magnetism; and this effect continued for a certain interval, beyond which the magnetization was again negative. When still more remote, it was positive, and continued so to all greater distances that were tried. Hence the action appears to be periodical with relation to the distance at which it is exerted.

(165.) The number of periods in these alternations, as well as the distances at which they occur, appear to depend upon a variety of circumstances of which it

* Silliman's Journal, quoted in the Journal of the Royal Institution, I. 609; and II. 182.

* Watkins, Popular Sketch of Electro-Magnetism, p. 46.

† Annales de Chimie, tome. xxxiv.

is difficult to appreciate singly the effect: such as the intensity of the electric discharge, the length of the straight wire, its diameter, the thickness of the needles, and their degree of coercive force. In general, when the wires are very slender, and the coercive force of the needles feeble, the periodical alternations above noticed are less numerous; and it even frequently happens, with these conditions, that the magnetization is every where positive, and that the only differences observable at different stages of distance, are those of greater or less intensity.

(166.) When the discharge from the electric battery is transmitted through a wire coiled into the form of a helix around glass or wooden tubes, a similar diversity is met with in the effects produced on different needles successively placed in the interior of the tubes, and in different situations relative to the axis. By varying the intensity of the charge of the battery, or the length or thickness of the needles, the nature of the result is changed. The maximum of magnetic intensity which may be produced by a given wire, depends on the ratio between its thickness and its length; so that the degree of magnetization amounting to saturation, bears a relation to the value of this ratio. The degree of magnetic power that a needle receives from the influence of an electric discharge, and even the direction of its magnetization, depend also on the nature and the dimensions of the bodies that are in contact with it, or that surround it.

(167.) The magnetizing influence of a helix through which an electric discharge is passed, is completely intercepted by a cylinder of copper, of sufficient thickness, inclosing the needle, and introduced within the helix. When the interposed cylinder is of less thickness, some magnetic effect becomes perceptible; and when the thickness of the copper cylinder is still farther reduced, the needle is rendered even more strongly magnetic than when exposed to the action of the helix without any interposed substance. Tin, iron, and silver, placed round the needle, produce a similar modification of the electro-magnetic action of the helix; when interposed in very thin plates, they increase this action; when of a certain thickness, they entirely intercept it. Cylinders composed of metallic filings do not produce this effect; whereas we again meet with the intercepting property, if the interposed substance is composed of concentric layers consisting alternately of metallic and of non-metallic bodies. It would thence appear that solutions of continuity in a direction perpendicular to the axis of the needle, or to the axis of the helix, have a considerable influence on the magnetizing effects of the latter upon the former. An influence of a similar kind has been observed from metallic plates of different thickness, placed in contact with a needle properly disposed with regard to a straight conducting wire receiving the discharge of an electric battery; being found, according to their size or position, to modify the intensity and even the direction of the magnetism acquired by the needle.

(168.) All these phenomena appear to depend on the suddenness of the action exerted by the electric shock, either directly on the particles it meets with in its course, or on objects that are situated at a distance in the surrounding space. But the direction of the magnetization, as to its being of the positive or negative kind, depends essentially on the intensity of the discharge; so that discharges of different intensities develope in the metal a set of opposite states analogous to the polarities of contrary signs, acquired at different distances from a conducting wire, or by different intensities of electricity.

Chapter XI.

Mutual Actions of Electric Currents.

§ 1.—*Action of Parallel Rectilineal Currents.*

(169.) The discovery of Oersted, and all the consequences we have developed from the fundamental law that appears to regulate the reciprocal action between electric currents and magnetic bodies, belong to that division of the subject to which the term *Electro-Magnetism* is more properly applied: for they refer to the relation subsisting between the two agencies of electricity and of magnetism, which we have been accustomed to consider as distinct from one another. But electric currents are also found to have a mutual action on one another: and this general fact, which was ascertained by Ampère, soon after the discovery of Oersted, esta-

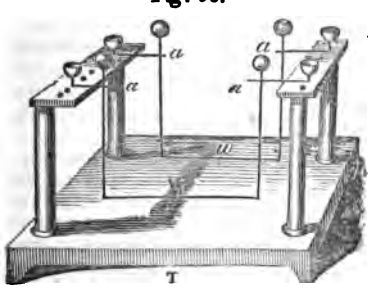
blished another great division of the science; and the law on which it is founded is no less prolific in its consequences, and important in its applications, than that we have hitherto been occupied in investigating. To this branch of the subject Ampère has given the name of ELECTRO-DYNAMICS.

(170.) When two conducting wires are suspended or supported in such a manner as to be capable of moving, either towards or from one another, at the time that electric currents are passing through them, they manifest a mutual attraction or repulsion, according as the currents are moving in the same or in opposite directions in the two wires. This action is variously modified, when the relative inclinations and positions of the currents are varied.

(171.) We shall begin by considering the simplest case, which is that in which the two currents are running in parallel directions. The attraction or repulsion of currents, under these circumstances, admit of being exemplified in a great number of ways, according to different modes in which the conducting wires are suspended and rendered moveable. Thus the wires in the apparatus described § 143 and 144, *figures* 92 and 93, may be employed for that purpose, by bringing either the vertical or the horizontal branches sufficiently near a straight wire, through which an electric current is also passing.

The following is also an apparatus for the direct exhibition of this phenomenon. T, *fig.* 96, represents a rectangular table from which arise four upright pillars supporting two cross pieces of wood, having a row of holes for receiving four cups, two on each piece, the

Fig. 96.



distances of which from each other may by means of these holes be varied at pleasure. Short wires, *a*, *a*, *a*, *a*, proceed horizontally from the bottoms of the cups, and serve as pivots round which the two wires, W, *w*, bent twice at right angles, are made to turn at the upper part of their vertical branches, having small holes drilled through them for that purpose. These wires, thus hung freely upon their pivots, carry on their upper ends small weights, which, bringing the centres of gravity as nearly as possible in coincidence with the points of suspension, enable them to be moved by a very slight force. Conducting wires, proceeding from a voltaic battery, are then inserted into the cups previously filled with mercury, in such a manner that the galvanic current shall pass in the same direction through both the parallel wires; the moment this is done, the wires move towards each other, even from a distance of several inches, exhibiting a powerful mutual attraction. When the currents are transmitted in directions opposite to each other in the two wires, which they may be made to do by transposing the communicating wires inserted into the cups leading to one of the moveable wires, while the others are left as before, the moveable wires immediately recede from each other, manifesting a repulsion as powerful as the attraction was in the former case.

(172.) The electro-magnetic forces obtained from voltaic batteries of the ordinary strength are so feeble when compared with the force of gravity, that, in devising experiments for exhibiting their action, it becomes necessary, in order to succeed, so to contrive the apparatus as that the parts to be moved by these forces may be as light as possible, and be also suspended in such a way as to occasion the smallest amount of friction. Attention should be given not to encumber the conductors, or the magnetic bars which are to be set in motion, with any superfluous materials capable of adding to their weight; and we should avoid such dispositions as require them to move in opposition to their own gravity. The surfaces which are intended to move through mercury should be as much as possible reduced; not only on account of the friction which takes place between the solid and the fluid, but also because the surface of the mercury rapidly oxidates, and the film of oxide thus formed opposes considerable resistance to the motion of a solid body, and greatly impedes the mechanical action of the apparatus. In general, it will be found that a vertical suspension by a point is

preferable to suspension by a horizontal axis, as the former occasions less friction. Thus Mr. Watkins finds, that the attractions and repulsions of wires transmitting voltaic currents are exhibited with more facility when they are suspended vertically, their two ends terminating respectively in upper and lower cisterns, than when turning horizontally, as in the apparatus exhibited in the pre ceding figure.

These attractions and repulsions may also be exhibited with a very feeble current of electricity, by means of the gold-leaf galvanoscope, already described, § 127. By removing the magnet, and inserting within the instrument a thick wire, inclosed within a glass tube, parallel and near to the gold leaf, a strong current may be passed through the wire, at the same time that a feeble current is transmitted through the gold leaf, which will then exhibit the attractions or repulsions of parallel currents, according as they are in the same or in opposite directions; for these actions take place equally whether the two currents are obtained from separate voltaic combinations, or whether they are merely two portions of the same current in different parts of its course.

(173.) This latter case occurs whenever a wire is coiled round in a spiral or heliacal form, so as to bring different portions of the same current, passing in the same direction, very near to one another. It occurred to the author of this treatise, soon after hearing of Ampère's discovery of the attraction of electrical currents, that it might be possible to render the attraction between the successive and parallel turns of a heliacal coil very sensible, if the wires were sufficiently flexible and elastic; and, with the assistance of Mr. Faraday, this conjecture was put to the test of experiment, in the laboratory of the Royal Institution. A slender harpsichord-wire bent into a helix, being placed in the voltaic circuit, instantly shortened itself whenever the electric stream was sent through it; but recovered its former dimensions the moment the current was intermitted. It was supposed that possibly some analogy may hereafter be found to exist between this phenomenon and the contraction of muscular fibres, which seems to be regulated by some properties of the nervous system, not unlike those of electric agency. Messrs. Prevost and Dumas have advanced a similar theory of muscular contraction, founded on a supposed distribution of nervous filaments, through which they imagine a current of electricity is sent, for the purpose of determining the action that precedes contraction. This theory, they conceive, is supported by microscopic observations; but it is far too hypothetical in its present form to deserve serious discussion.

(174.) The general fact of the mutual action of electric currents being established by these and similar experiments, we must proceed to consider the different modifications it receives by a variation of circumstances regarding the quality and direction of the currents.

(175.) We possess as yet but an imperfect knowledge of the peculiar affections which electricity experiences when in motion, and which enable it to exert the singular species of action we are here investigating, so different from its attractive and repulsive powers when at rest. These two classes of effects obey laws not only different, but in some respects of an entirely opposite nature. Accumulated electricity, when not in motion, acts in a degree proportioned to its tension; but the wires, which are silently conducting a current of electricity in motion, exhibit no sign whatever of electric tension; they produce no change in the electrometer, and neither attract nor repel light bodies in their vicinity. The law of action in the state of rest is, that dissimilar electricities attract, and similar electricities repel one another. When in motion, on the contrary, it is between similar currents, that is, currents moving in a similar manner, that attraction takes place; while a mutual repulsion is exerted between dissimilar currents. The electro-statical effects of electric tension cease when the atmospheric pressure is removed; but the electro-dynamical effects of currents take place equally whether the conductor be surrounded by the air or placed in *vacuo*.

(176.) Since the effects of electric currents are the consequences of the motion of the electricity, it is natural to suppose that they will be in proportion to the velocity with which it moves, as well as to the quantity that is set in motion. But we are in utter ignorance of the real velocity with which the electrical effects are propagated along a conduct ing body, during the completion of the voltaic circuit: nor do we even know

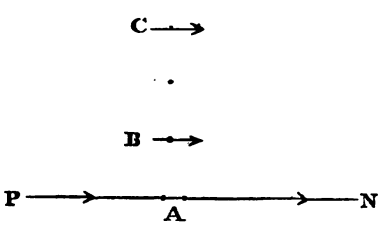
whether this velocity varies in different cases, nor have we any distinct idea of the causes that are likely to produce such variation. We can perceive, however, that the mode of transmission has a considerable influence on the results. The currents transmitted by perfect conductors are *continuous;* that is, their intensity is either constant, or varies insensibly during two consecutive instants. When the conductors are imperfect, the currents are *discontinuous;* for the electricity is allowed to accumulate for a certain time, and until the insulating force is overcome, when it escapes, and passes on with a sudden impulse, analogous to an explosion. The electro-motive power continuing to act, gives rise to a second accumulation, and a fresh explosion, and so on successively. These alternations may become sufficiently rapid to escape our senses, and thus produce the appearance of an uninterrupted current, although it be really discontinuous. The distinctive character of such currents is, that they are incapable of producing a deviation in the magnetic needle. This is the case with the current produced by the common electrical machine, when a communication is established between its positive and negative conductors: and also with the currents established in what have been called the *secondary piles* of Ritter (see *Electricity*, § 93), or piles constructed with a series of metallic discs separated by humid conductors. Discharges from the Leyden vial, in like manner, although they induce a degree of permanent magnetism in steel bars near which they pass, yet scarcely leave any traces of their effects on the needle of the galvanometer, when transmitted through the wires of that instrument.

(177.) The continuity of the electric current being the quality most immediately concerned in the production of the effects that are the subject of our present consideration; and it being impossible for us to discriminate differences of velocity or of quantity, in any other manner than by the total effects that result from the passage of the current through a conducting body, we shall distinguish continuous currents only in respect to their *intensity*, and pretend to judge of the degrees of intensity solely by the amount of the effects produced on the galvanometer.

(178.) In order to arrive at the fundamental law of electro-dynamic action of currents upon one another, it is necessary to consider the total action of each as resulting from the combined actions of every one of its parts. As it is not possible to institute a direct measurement of those elementary forces exerted by each indefinitely small portion, the one upon the other, the inquiry can only be made by assuming some hypothesis relative to the law of diminution according to distance, and prosecuting the consequences of such an hypothesis, when applied to such finite portions of current as occur in our experiments, and to compare them with actual observation, their accordance with which will be a test of the admissibility of the hypothesis.

(179.) Guided by the analogy of all the other known forces in nature, we shall assume that the mutual actions of the elementary portions of electric currents are inversely as the squares of their relative distances; and this is, in fact, the supposition which agrees best with all the facts that have hitherto been ascertained. If we suppose A, for instance (*fig.* 97), to be an indefinitely small portion of the rectilineal current P N, moving from left to right, it will act upon another elementary portion, B,

Fig. 97.



of a current placed at a given distance with nine times the energy that it exerts upon a similar portion of current placed at C three times further removed from it. If we call the force of attraction f the intensity of the first current a, and of the second current b, and the distance between them, or the line B A, d, the following equation will express the law just enunciated:—

$$f = \frac{a\ b}{d^2}$$

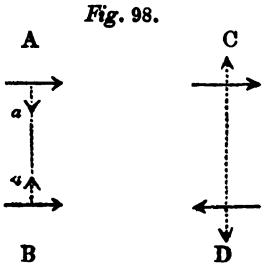
(180.) It may be demonstrated mathematically, that such being the law of elementary action, it will follow as a necessary consequence that the total

action of a current, P N, extended to an infinite length, upon an elementary portion of a parallel electric current placed at any given distance from it, is in the simple inverse ratio of the shortest distance between them—that is, of a line drawn from the one to the other, and perpendicular to both. Thus, in the example just given, where the distance C A is three times the distance B A, the action of the indefinite current P N is three times greater upon B than upon C. So that if this total action be expressed by F,

$$F = \frac{a\,b}{d}.$$

(181.) The action, whether attractive or repulsive, of two elementary portions of current, must be conceived as exerted in the direction of the line which joins them, and which, for the sake of distinctness, we shall call the *medial line*. So that in the case of the parallel currents A and B, *fig.* 98, moving in the same direction, an attraction denoted by the short arrows *a* and *a*, takes place in the

Fig. 98.



direction of the medial line A B; and in the case of the currents C and D, likewise parallel, but moving in opposite directions, a repulsion takes place, as shown by the short arrows, in the direction of the same line. It should be observed that, in both cases, the *action on each current is perpendicular to the direction of that current.*

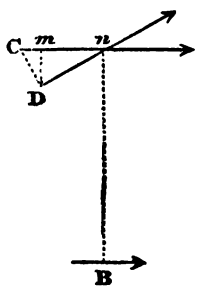
§ 2. *Action of inclined Rectilineal Currents.*

(182.) Let us next suppose that the two currents, still remaining in the same plane, the direction of one of them, A, *fig.* 99, is changed from parallelism to the position C *c*, the action will still be perpendicular to that position—that is, the current A will be urged to move in the line A *a*, at right angles to C *c*; but the force which thus impels it will be diminished in the ratio of radius to the sine of the angle B A C, which the direction of the current makes with the medial line A B. This will readily appear by resolving the force A *b* into the two forces, A *a*, A C, of which the latter, acting counter to the direction of the current, is destroyed, while the only effective force is A *a*, which is to A *b* as the sine of B A C to radius.

Fig. 99.

(183.) A similar diminution of the force by which the current A reacts upon B, takes place in consequence of its obliquity; for the portion C *n*, *fig.* 100, which, when it was parallel to B, acted with its full power, has only the

Fig. 100.



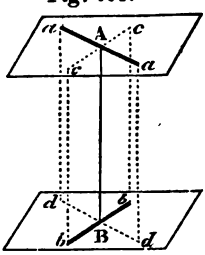
force of the portion *m n*, when acting in the oblique position D *n*, the diminution being proportional to the cosine of the angle C *n* D, or, what is the same, to the sine of the angle D *n* B. The mutual action of the current, therefore, situated in the same plane, but in oblique positions, may, in as far as this obliquity is concerned, be expressed by the following equation, in which α and β denote the angles made by the directions of the currents respectively with the medial line.

$$f = \sin.\ \alpha.\ \sin.\ \beta.$$

(184.) Let us now inquire into the modification the formula must receive when the two currents are in different planes. We have seen that in the last

instance, the effective force of an oblique current, in its action on another current, is obtained by reducing that force to a direction at right angles to the medial line. Let us suppose this to be done with regard to both the currents A and B, *fig.* 101, the former being reduced to the line *a a*, and the latter to the line *b b*, situated respectively in planes perpendicular to the medial line A B. The force

Fig. 101.



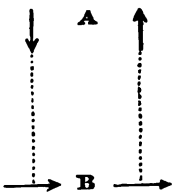
a A, estimated in the direction A *c*, drawn parallel to B *b*, or the force B *b* estimated in the direction of B *d*, drawn parallel to A *a*, will, in either case, be reduced in the proportion of radius to the cosine of the angle *a* A *c*, or *d* B *d*, which is equal to it, and which may be defined, the angle between two planes passing through the medial line and each of the currents respectively. Calling this angle μ, the formula, including all possible relative positions of the currents, either in the same or in different planes, becomes when the intensities and distance between the currents are also taken into account,

$$f = \frac{a\, b\, (\sin.\, \alpha.\, \sin.\, \beta.\, \cos.\, \mu.)}{d^2}$$

which should express the action of the currents estimated in the direction of the medial line, provided the hypothesis with which we set out were correct.

(185.) But experiment, the only criterion of the soundness of physical theories, shows that an element is still wanting in this process for estimating the value of the forces. It would follow from the above formulæ that when an elementary portion of a current A, which has the precise direction of the medial line, that is, when it proceeds in a straight line, either towards or from another elementary portion of a current B, *fig.* 102, no action can take place between them; for the angle α being reduced to nothing, its sine likewise vanishes: and the same result should also obtain when the planes in which two currents are situated are at right angles to one another: for

Fig. 102.

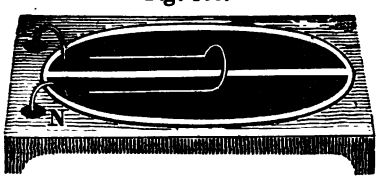


in that case the cosine of μ vanishes, and the whole function expressing the value of f is reduced to zero. This destruction of force ought to take place, whatever be the position of the force B.

(186.) This, however, is not found to be the case, excepting only when the current B is at right angles to the medial line. If it be in any other position, and more especially if it also coincide in direction with the medial line, a repulsion is manifested. This will appear from the result of the following experiment:—

(187.) Let a flat oval dish of glass, or porcelain, *fig.* 103, be separated into two divisions by a glass partition, fixed with cement, and the divisions filled with mercury. Insert into each of these troughs, the sides of a copper wire, bent in the manner shown in *fig.* 103, so that they may be parallel to the partition,

Fig. 103.

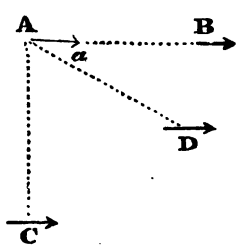


over which the arc passes, joining the two parts of the wire which float in the mercury. Every part of this wire, excepting the steel points soldered to its extremities, is to be covered with silk. Two wires, forming connexions with the two poles of a powerful voltaic battery, being inserted in the cups P and N, which communicate with the mercury in the basin, in the directions of the straight branches of the wire produced, the current from the one will pass through the mercury in the adjoining partition to the steel point belonging to one of the extremities of the wire, and then, circulating through the whole extent of the wire, will pass out into the mercury of the partition, and be carried off by a third wire. It is found that at the instant this current is established, the wire moves in

the direction of the long branches until it is stopped by the end of the vessel *. This repulsion is exerted, not only at the indefinitely small distance that occurs between the parts immediately in succession, but also at finite distances between all the parts of the same current.

(188.) Since it appears, from this and other experiments, that portions of the same, or of different currents, moving in the same continuous line, or at oblique angles, repel one another, Ampère found it necessary to introduce another term in the formula. Since the action due to this cause is greatest when the two currents are in the same continuous line, as A B, *fig.* 104, and vanishes when the medial line is at right angles to both of them, as in the positions A and C, he inferred that in all intermediate positions, as at D, for instance, the action would be proportional to the cosine of the angle B A D, between the direction of the current A, and the medial line A D, which we have already expressed by the symbol α. The same reasoning applies to

Fig. 104.



the current D, when the variations of its position are taken into account. The term to be added to the force, as formerly determined, must therefore be some function of the cosines of the angles α and β, and may be expressed by prefixing to them the indeterminate coefficient k. So that we now have

$$f = \frac{ab}{d^2}(\sin.\alpha.\sin.\beta.\cos.\mu + k\cos.\alpha.\cos.\beta).$$

(189.) In his earlier speculations, Ampère had regarded the value of k as so small that it might safely be neglected; but subsequent researches led him to the conclusion that it is in reality equal to $-\frac{1}{2}$, so that the whole of this second term of the formula is negative, when the cosines of the two angles are themselves positive.

* Ampère, Théorie des Phénomènes Electro-Dynamiques, p. 39

(190.) The electro-dynamic forces which are thus called into action by voltaic currents, and of which the intensities and directions are determined according to the laws above defined, are subject to the same laws of composition and resolution as all other mechanical forces, and present the same facilities for the application of mathematical reasoning. It would of course be impossible to attempt giving, within the limits of this treatise, even an outline of the analytical investigations by which various important conclusions have been deduced. We must content ourselves with stating merely results, referring such of our readers as desire further information on the subject to the works of Ampère, Biot, and Savary.

(191.) It follows evidently from what has been said, that when two electric currents, situated in the same plane, are inclined to one another at any angle, they are always mutually repulsive when one of them approaches to, and the other recedes from, the summit of the angle; and, on the contrary, they attract one another when they both approach to, or both recede from, that angular point. When the intensities and positions of the currents are the same in the two cases, and the only difference is in the change of the direction of one of the currents, then the attractive force in the latter case will be found to be precisely equal to the repulsive force in the former case. And, universally, whatever be the action of a system of fixed conductors upon a moveable conductor, it is immediately changed into an equal and contrary action, by reversing the direction of the current, through either the moveable or the fixed part of the system. If the direction of the current through both the parts be reversed at the same time, the original action is reproduced. In this way we obtain a criterion by which the mutual actions of different parts of any electro-dynamical apparatus may be distinguished from those depending on the influence of the earth. The former effects are permanent, but the character of the latter is changed by reversing the direction of the current throughout the whole system.

(192.) It is hardly necessary to enter into any minute description of the apparatus by which these conclusions may be experimentally verified. The modes of suspension adapted to the particular object of the experiment will readily occur to any one who has made himself

acquainted with the details we have already given of analogous experiments. It will be sufficient to observe that there are, in general, two kinds of rotation of which the moveable parts of the apparatus are susceptible, the one on a vertical axis, as in figures 66, 71, 84, 91, 92, 93, and the other on a horizontal axis, as in figures 85 and 96.

(193.) Care should always be taken, in nice experiments, to guard against the errors that might arise from allowing the influence of the earth to interfere with the actions we are examining. This disturbing force may, in general, be neutralized, and rendered ineffective by particular dispositions of the conducting wires. Thus the moveable conductor, *fig.* 92, may be rendered *astatic* or independent of terrestrial influence, by forming a second parallelogram below the first, composed of wires, so turned as to oblige the current to pass in opposite directions in corresponding parts of each. This is shown in *fig.* 105, in which P and N represent the steel points affixed to the extremities of the wires for the purpose of being placed in cups with mercury; and the directions of the currents in the several portions of the wire are indicated by arrows, whereby it appears that the action of the earth upon any one part is neutralized by its equal and opposite effect in another corresponding part, similarly situated with regard to the axis of rotation. The wires should be covered with silk thread, in order to prevent metallic contact in the parts where they are brought together. The shaded parts represent the branches that may be conveniently tied, or simply twisted together, after this precaution has been taken, for the sake of greater firmness. The weight W is applied as a counterpoise on the other side of the axis of rotation.

Fig. 105.

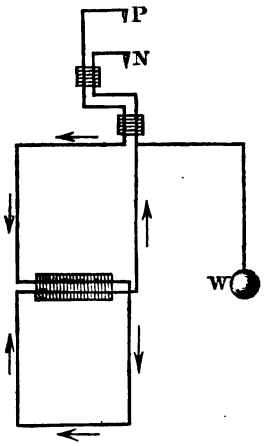


Fig. 106.

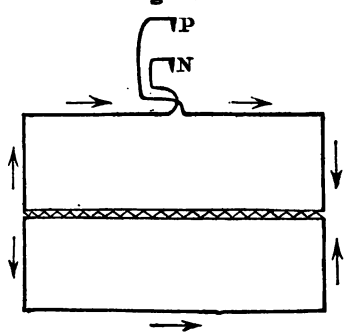
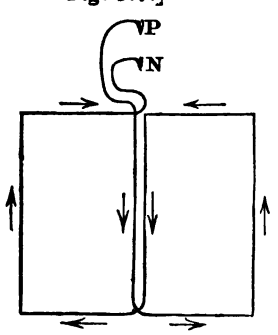


Fig. 107.

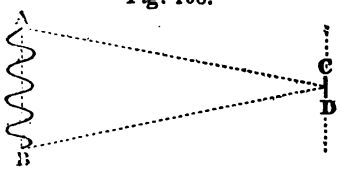


(194.) *Fig.* 106 represents another form of an astatic conductor, having the same properties as the preceding, but better adapted for the examination of the actions on the lower horizontal branch.

(195.) *Fig.* 107 shows an arrangement of a similar kind, in which the horizontal branches neutralize one another, but in which the interior vertical branches, being in the axis of motion, have no influence in producing rotation; and the exterior vertical branches are therefore uncompensated, as far as relates to the action of any current presented to them: although being in opposite sides of the axis, they neutralize one another as far as regards the influence of the earth.

(196.) It follows, as a consequence of the principles already laid down, that the action of a small portion of conducting wire, bent into any number of flexures, provided they extend to no considerable distance, upon another current, anywhere situated, is equivalent to the action of a similar wire proceeding in a straight course between the two extreme points of the contorted wire. The action, for example, between a conducting wire, A B, *fig.* 108, and an elementary portion, C D, the one pursuing a sinuous course, the other recti-

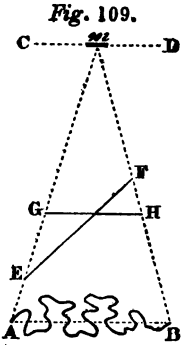
Fig. 108.



lineal, is precisely the same as if the former, instead of being contorted, had passed in a straight line from the point A to the point B; that is, along the dotted line A B.

(197.) By an extension of the reasoning which led to the conclusion just stated, it may be proved that the action of a current traversing the contorted line A B, *fig.* 109, (and which we have seen is equivalent to that of a current

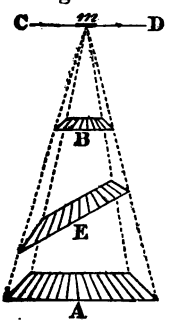
Fig. 109.



of equal intensity passing in a direct line from A to B,) on any elementary portion m of a distant current C D, will be to the action of a similar current E F, (comprehended within the angle A m B, which A B subtends at the point m, the middle of the elementary current,) in the inverse proportion of their mean distances from the point m; that is, drawing G H, making equal angles with A m and B m, through the middle of E F, the action of A B is to the action of E F, inversely as A m to G m.

(198.) If the electric currents be conceived as spread over a given surface, A, *fig.* 110, instead of being confined to a single line; then the action of this superficial stratum of currents on the elementary current m, which is a part of

Fig. 110.



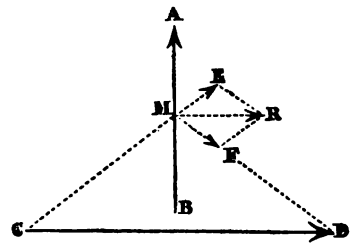
the current CD, will be precisely equal to that of B, or E; or of any other superficial stratum composed of similar currents, situated at any distance from m, and inclined at any angle, provided it be comprehended by the sides of the same pyramidal or conical figure, having the surface A for its base, and m for its apex. This, indeed, follows as a necessary consequence of the preceding law: the diminished influence of the currents in A, resulting from their greater distance, being exactly compensated by their greater number. It may be derived still more directly, indeed, from the general law of the action of electric currents being inversely proportional to the squares of the distances. We shall have occasion hereafter to make important applications of this principle.

§ 3. *Action of Terminated Currents.*

(199.) We have seen that the action of a rectilineal current of infinite length on a short portion of current at a distance, situated in the same plane, and wholly on one side of the former, tends to give it motion in a line perpendicular to itself, and either in the same direction as the extended current, or in the opposite direction, according as it is receding from or approaching to it. The same applies to a current of any length, provided it be situated wholly on one side of the cur-

rent that acts upon it, and which it will be convenient to designate a *terminated current*. Thus, the current A B, *fig.* 111, lying wholly on one side of the extended current C D, and which is therefore a terminated current, will be urged

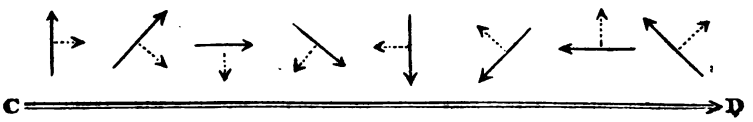
Fig. 111



in the direction of the dotted line M R. For since the current A B is moving from the angular point B towards A, while the current C D is, in the part C B, moving towards B, the former will be repelled by the latter during the whole of that part of its course. The resultant of all the repulsive forces thus operating on A may be represented by the line M E. On the contrary, the currents passing along the lines A B and B D, are both moving in a direction from the angular point B; consequently they attract one another; and the resultant of these attracting forces may be expressed by the line M F, which, when combined with M E, gives the total resultant M R, perpendicular to A B.

(200.) Applying this principle to various positions of a terminated current with relation to the extended one, we obtain results which are expressed in the annexed diagram, *fig.* 112; where, as before, C D is the extended current passing from C to D, and the upper lines represent various positions of the terminated currents, of which the directions are marked by the terminal arrows; while the dotted arrows point out the directions of the resulting mo-

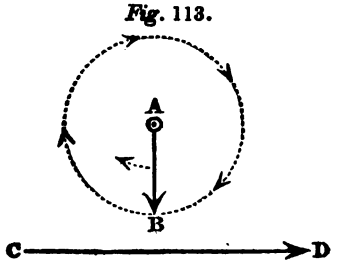
Fig. 112.



tions. As a general rule, whenever the direction of the terminated current is *from* the line of the extended current, it is urged to move in the same direction as the extended current moves; when its current is *towards* the extended current, it is urged to move in the contrary direction.

(201.) It is easy to perceive that if, instead of allowing the conducting wire transmitting the terminated current to obey its tendency to move parallel to itself, its motion were restricted to rotation round a fixed axis at one of its extremities, as shown in *fig.* 113, the force arising from the action of the in-

Fig. 113.



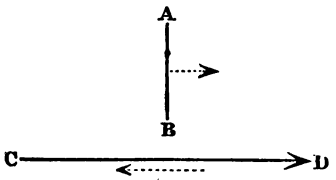
definite current C D, will carry the terminated current round the whole circumference of the circle. This rotatory force is independent of the angle of inclination of the currents, and is, consequently, uniform in every position of A B; and will accordingly act as an uniformly accelerating force, causing the wire to revolve with continually increasing velocity, until checked by friction and other mechanical obstacles.

(202.) The direction in which the wire revolves depends, of course, upon the relation between the directions of the two currents concerned. When the terminated current is passing from the centre to the circumference in the shorter wire, its revolution will be as represented in the figure; that is, in a direction contrary to that of the unlimited current, in that part of the circle which is nearest to it, but similar to it in the more distant part of the circle. The reverse takes place when the current in A B is passing from the circumference to the centre.

(203.) While such is the action of the

extended current upon the one that is terminated, an equal but contrary reaction is necessarily exerted by the terminated one upon the extended current. Thus, while the current A B, *fig.* 114,

Fig. 114.



tends to move in the direction of the upper arrow, its reciprocal action on the current C D, urges the wire that conducts it in the contrary direction, from D to C, as denoted by the lower arrow; and the same principle applies to all the other cases.

§ 4. *Action of Diverging and Converging Currents.*

(204.) Since the rotatory force is the same in all positions of the wire, it is evident that if wires, or other conducting bodies, be so disposed as to cause the currents to radiate from a centre in all directions, they will tend to revolve in the same manner as any one of them singly would have done, by the influence of a rectilineal current in the vicinity, and in the same plane; provided this latter current be wholly without the circumference of the circle of revolution. The same thing will happen when the currents converge from the circumference to the centre, only the direction of the motion will be reversed. These two conditions of the experiment are represented in *figs.* 115 and 116, where the arrow-heads in the paths of the currents denote their direction; and the exterior dotted arrows the direction of the revolution of the conductors.

Fig. 115.

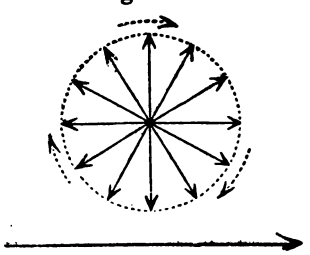
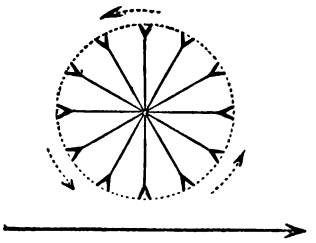


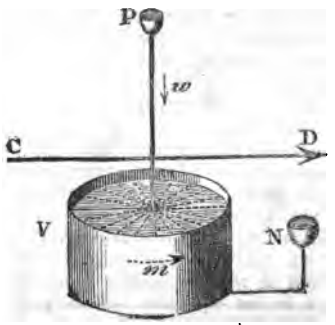
Fig. 116.



(205.) Examples of this kind of divergence or convergence of currents frequently occur in electro-dynamical experiments. They are met with whenever a fluid conductor, such as mercury, is the medium of communication between the point of a conducting wire dipped into the fluid and a circular rim of metal; in which case there is always more or less of diffusion of currents while they are passing through the fluid; and generally there is a tolerably regular radiation or concentration of the currents, of which some idea may be formed by *fig.* 117; where the current passing from P to N, through mercury contained in the cylindrical vessel V, will radiate from the point of the wire towards every part of the circumference of that vessel. If the current pass from N to P, it will converge towards the wire. In either case the action of a strong current, passing along the straight horizontal conductor C D, will give rise to a revolving motion in the mercury, the direction of which, corresponding with the directions of the two currents, is indicated by the arrows at *w*, D, and *m*.

(206.) It is not easy to exemplify by direct experiment the theoretical deductions applicable to the case of the action of a straight current of indefinite

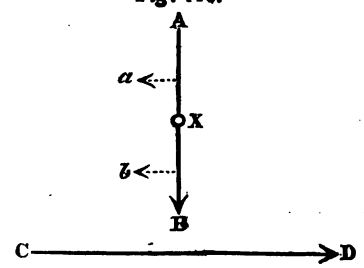
Fig. 117.



length on a terminated current; that is, on a portion of another current, situated on one side only. The difficulty arises from the impossibility of limiting the actions to those parts of the currents to which we wish to confine them, while studying their effects, and of excluding the action of the remaining portions of the currents necessary for completing the circuit. The only mode of preventing the interference of the latter, is to neutralize them by opposing one part to another; this may in a great measure be accomplished by providing for the subdivision and branching off of the currents in different directions, so that their actions may destroy one another. If, for instance, the ends of the smaller wire that is to be rendered moveable, be made to dip into a vessel of mercury, of sufficient width to allow of the electric currents to diverge and spread over a considerable surface, they will not materially interfere with the actions we are examining.

(207.) In the cases we have just considered, (§ 204,) the axis of rotation in the shorter wire was supposed to be at its extremity. If its situation were different — were it, for example, in the middle of its length, as at X, *fig.* 118, it is evident that when the current is passing from A to B, it moves in the first portion towards the

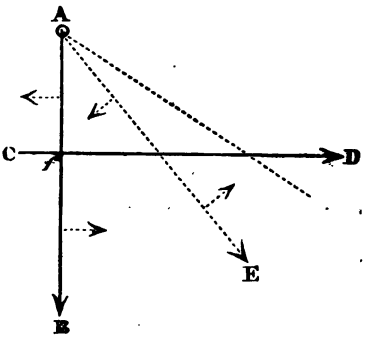
Fig. 118.



centre, and in the second portion from it; hence the rotatory forces, denoted by the arrows *a*, *b*, counteract one another, and the wire is urged to revolve only by the difference, if there be any, between them.

(208.) If the current, which we have hitherto supposed to be terminated, that is, altogether on one side of the rectilinear current, were prolonged so as to cross the latter (without, however, joining it), that portion which extended beyond it would have a tendency to move in an opposite direction to the part on the other side; so that these rotatory forces would oppose each other; and as the strongest would prevail, it would bring the conductor into a position where they are in equilibrium. See *fig.* 119, where the portion *f* B of the limited

Fig. 119.



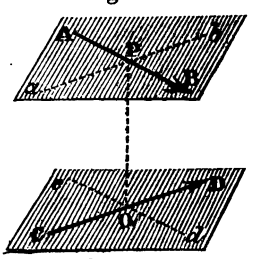
rectilineal current A B, turning on the axis A, and crossing the unlimited current C D, tends to move in a contrary direction to the portion A *f*, the position of equilibrium being that of A E.

(209.) If the current A B be traversed by the current C D passing through the axis itself, A, the position of equilibrium is that of parallelism between the two wires. In either case there can be no revolution round the axis.

§ 5. *Action between Currents situated in different Planes.*

(210.) Let us now consider what will happen when the two currents A B and C D, *fig.* 120, are in different planes, both being of an indefinite length, and extending on both sides of the perpendicular line P Q, which is common to the directions of both currents, and divides each into two portions. At-

Fig. 120.



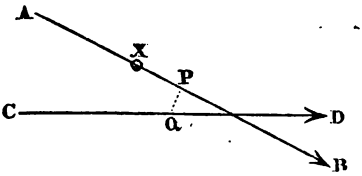
traction will take place between those portions in which the current is passing towards P or Q, the points at which the currents are nearest to each other; that is, in the present instance, between the

portions A P and C Q. The portions P B and Q D will also attract one another, because the currents are proceeding from the points P and Q, in each respectively. But the portions A P and Q D will repel one another, as will also the portions P B and C Q; because the currents are moving in a different manner in the two that compose each of these pairs.

All these forces concur in producing a rotatory motion round the axis P Q. The wire A B will tend to assume the position *a b*, parallel to C D; and the wire C D will be urged to take the position *c d* parallel to A B. If only one of these be moveable, it will place itself in a line parallel to the other; if both be moveable, they both will take an intermediate position; so that, in either case, they will become parallel to one another. That part of the force which produces this rotatory effect, and acts in a plane perpendicular to the axis, may be termed the *directive force*. It varies as the sine of the angle A P *a*; but another part of the force still remains, namely, that which acts in a direction perpendicular to this plane—that is, parallel to the line P Q, the nearest distance of the wires. It is evident that this force varies as the cosine of the angle A P *a*. Whenever that angle is less than a right angle, this force is attractive; and as it tends to bring the currents nearer to each other, it may be distinguished from the former by the designation of the *approximative force*. Commencing when the positions of the wires, from being perpendicular, are slightly inclined to each other, this latter force attains its maximum when they have been brought by the directive force into a parallel position. When the corresponding portions of the wires, on the other hand, form an obtuse angle, the approximative force is negative, and is so in the greatest degree when the wires are parallel, so that their currents move in opposite directions. This is an obvious consequence of the change of sign which the cosine of the angle A P *a* experiences when the latter changes from an acute to an obtuse angle.

(211.) If the movements of either of the wires be restricted to rotation round an axis different from P Q, such as X, *fig.* 121, some part of the directive force will be destroyed by the opposing action of the current passing through the portion X P, which intervenes between the axis and the perpendicular. This opposition of forces will increase according as the axis is further removed from the perpendicular: so that all action may

Fig. 121.

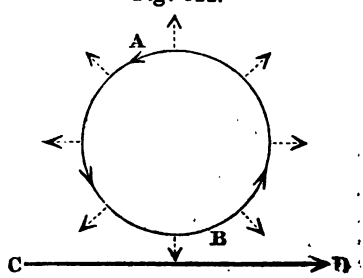


come to be entirely neutralized, if its distance is sufficiently great in proportion to the length of the other branch, P B, of the current situated on the other side of P Q. In estimating the resulting effect, however, it is necessary to take into account the mechanical advantage which the rotatory force, impelling the remote part P B, has over that which impels X P, in consequence of the greater length of lever by which it acts. When the contrary rotatory momenta thence arising are equal, the currents will be in a position of equilibrium, which position will tend the more nearly to coincide with that of parallelism, in proportion as the axis approaches to a coincidence with the perpendicular P Q. This result may be verified by employing the apparatus *fig.* 106, which, from its construction, is, as we have seen, astatic, and by which we may study the action of a transverse current upon either of the horizontal branches to which it is presented.

§ 6. *Mutual Action of Rectilineal and Curvilineal Currents.*

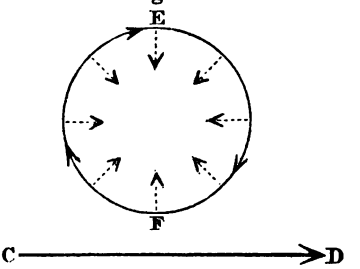
(212.) If a terminated current, which describes a curve line, be subjected to the action of an unlimited rectilinear current, its different portions will be urged in different directions, each being perpendicular to the respective portion of the curve. Thus the different parts of the circular conductors A B, *fig.* 122,

Fig. 122.



or E F, *fig.* 123, through which an electric current is passing, will be urged by the straight current C D, situated in the same plane with it, in the various directions indicated by the dotted arrows. If these forces were all equal, or nearly

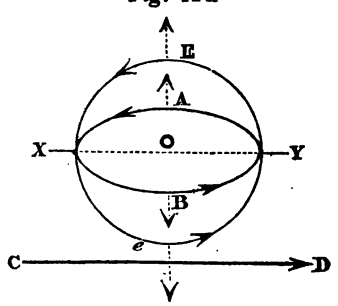
Fig. 123.



so, which could only happen when C D was at an infinite distance, or one incomparably greater than the diameter of the circle, they would all be in equilibrium. But, in all other cases, portions of the circles nearest to the current will be more powerfully acted upon than the remoter parts, and the forces by which they are impelled will therefore prevail, and the whole circle will tend to approach or recede from C D, according as the direction of the currents in that part is similar or contrary to that of the current C D. Thus it appears that the *approximative* force is equal to the difference between the resultants of the attractive and repulsive forces.

(213.) If the circular conductor be now made to revolve on an axis X Y, *fig.* 124, parallel to C D, and if it be

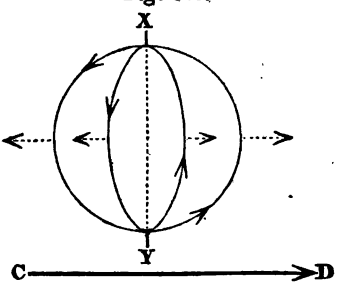
Fig. 124.



turned on this axis so that its plane is inclined to that which passes through its centre O, and the rectilinear current C D, the directions of the forces at A and B, being out of the plane of the circle, may be decomposed each into a force in that plane along the radius of rotation, and into one at right angles to it. The latter of these forces will tend to produce rotation, and to bring back the circle into its position of stable equilibrium E *e* in the plane common to it and to the current C D. Hence the *directive* force, or that which tends to bring the circle into this position, by turning it on its axis, is composed of the sum of the resultant forces acting upon the portions on each side of the axis. As the two sets of forces conspire to produce the same rotation, it matters not, as to the ultimate effect, whether or not the axis pass through the centre of the circle, provided it be parallel to C D, and either within the circle or beyond it, because, in the latter case, where there is an opposition of rotatory forces, the force acting on B being greater than that which acts on A, and also acting at a mechanical advantage, will always prevail.

(214.) Let us next suppose the axis X Y of the circular conductor to be at right angles to C D, as represented in *fig.* 125. The position of equilibrium will, under

Fig. 125.

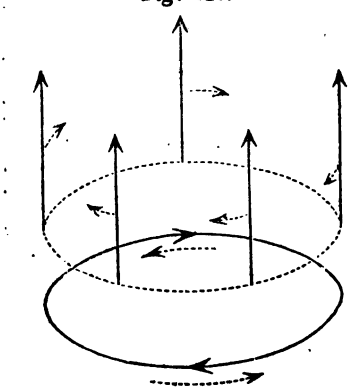


these circumstances, be precisely the same as the former: for any disturbance from the situation of the circle in which its plane includes the current C D, would give rise, in the portions of the circle nearest to it, to rotatory forces that tend to bring it back to that plane, as may be understood from what was explained in § 210. These forces will be aided by those that act on the lateral portions of the circle, in which an attraction exists towards those portions of the straight current where the directions correspond, as far as regards the approach to, or recession from the nearest points of the two conductors. The only forces opposing these are the forces acting upon the remoter parts of the circle, which are of course too weak to change the nature of the effect resulting from the former.

(215.) Whatever be the action which the circular current receives from the rectilineal one, a similar and opposite action is exerted by it on the latter, which is urged to assume a position in the plane of the circle, and such that the adjacent currents in each may be moving in similar directions.

(216.) The action of a circular current upon a rectilinear, but *terminated* current, situated wholly on one side of the plane of the circle, and inclined to it at a given angle, requires especial notice. If the direction of the straight current, when prolonged, pass near the centre of the circle, the forces that act upon it are nearly balanced, and neither action nor reaction is perceptible. If it be near the circumference, the action of the adjacent portion of that circumference will predominate, and effects, similar to those taking place between a terminated and an unlimited current, will be produced, with this modification, however, that the unlimited current being circular, the motion of translation in a straight conductor at right angles to the plane of the circle, following the course of the circumference, becomes itself circular; and if the conductor be attached to an axis perpendicular to the plane of the circle, and passing through its centre, that conductor will be made to revolve continually around that axis, as shown in *fig.* 126, where C D is the circular current, and A B the straight moveable, but terminated current. This rotatory force

Fig. 126.



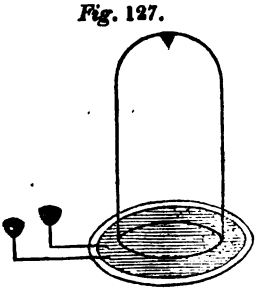
extends its influence beyond the interior of the circle to any distance, provided the straight current do not pass beyond the plane of the circle. The reaction of the straight current on the circular conductor impels the latter to revolve in the contrary direction, as marked by the dotted arrows parallel to it.

(217.) All these effects will be considerably increased if a great number of similar currents be moving in the same direction in the different parts of the circuit, described by the straight current in the last paragraph. This may be obtained by making currents traverse a number of wires placed in the surface of a cylinder, and parallel to its axis, which is also that of the rotation; or, what will be equivalent to this arrangement, by making a current pass along the surface of a hollow conducting cylinder, in the direction of its length; for in that case, the current may be considered as dividing itself into an infinite number of parallel filaments.

(218.) A similar augmentation of power may be obtained by multiplying the circular currents, either by employing a wire coiled into the form of a ring, or into that of a flat spiral. When these rings or spirals are combined with the cylinders above mentioned, the effects are again proportionably increased.

(219.) The modes of exemplifying these conclusions experimentally are various. Thus, a wire, as shown in *fig.* 127, consisting of two vertical branches, united above by a transverse arch, to

Fig. 127.



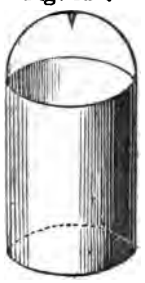
the centre of which is affixed a steel point turning downwards, for the purpose of suspension, may be united below to a circular rim, which dips into a shallow trough of mercury, so as to enable us to transmit currents through the wire, that will move in both the vertical wires in the same direction; that is, either upwards or downwards in both. If, while so suspended and connected, a circular current be made to act upon it from below, whether by means of a single circle, as shown in the same figure, or by a spiral coil, as that of *fig.* 128, the wire will revolve round its axis of suspension, in a direction deter

mined by the relative direction of the current.

Fig. 128.

(220.) A hollow cylinder, *fig.* 129, balanced in a similar manner as that of *fig.* 123, may be substituted for the wire; but its revolution will in general

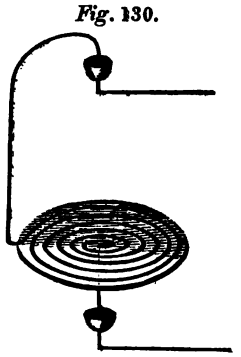
Fig. 129.



not be so rapid as the wire, because, although it may convey a more powerful current, the weight to be moved is also proportionably increased.

(221.) The rotation of the circular or spiral conductor may in like manner be exhibited by suspending either of them from a point in the axis of the circle, as in *fig.* 130, and subjecting it to the action of

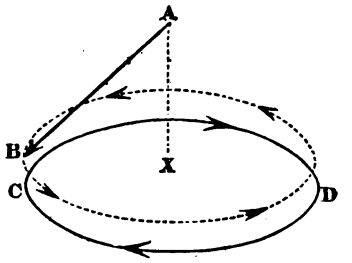
Fig. 130.



a terminated vertical current, that does not extend to both sides of its plane.

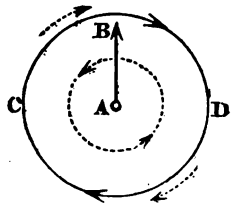
(222.) The effect is the same at whatever angle the direction of the straight current is inclined to the plane of the circular current, provided the axis on which it revolves be perpendicular to that plane and pass through its centre. Thus, if the wire A B, *fig.* 131, moveabl round on an axis, A X, be subjected to the action of a circular current C D, the plane of which is wholly below it, it will revolve, describing a conical surface.

Fig. 131.



(223.) Pursuing this investigation, it becomes evident that a revolving motion will equally take place, if the straight conductor be parallel to the plane of the circle, provided it does not exceed in length the radius of the circle. Thus, the straight conductor A B, *fig.* 132, which is wholly within the circle C D, revolves round the axis A, in the

Fig. 132.



same direction as the current in that circle, when its own current is passing from the circumference to the centre. When its current passes from the centre to the circumference, it will revolve in a direction contrary to the motion of the current in the circle. On the other hand, if the straight current be fixed, and the circle moveable round its centre, the action of the former will cause the latter to revolve in directions opposite to those which have been just stated.

(224.) It may be observed that we have limited this proposition to the cases in which the current A B does not extend beyond the circumference of the circle; for if it did, as seen in *fig.* 133, the exterior portion A B, being affected in an opposite manner from the interior portion B C, there would arise an opposition among the rotatory forces; and the amount as well as direction of the resulting motion would be regulated by the difference between them. This

contrariety of effect will, on the other hand, be removed, if the straight current be wholly exterior to the circle, as A B, *fig.* 134, though still moveable round the same axis as before. The revolution will now be performed in a direction contrary to that of the interior current in the former case. The reaction of an exterior current on the circular conductor will likewise be in the opposite direction to what it was before.

Fig. 133.

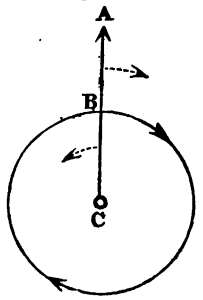
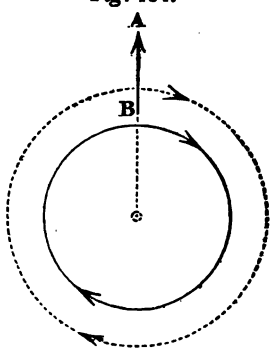


Fig. 134.



(225.) It is obvious that every thing that has been stated with regard to straight currents, the direction of which is towards or from the centre of the circular current, applies also to a number of radiating or converging currents.

Hence if the cylinder, *fig.* 129, communicating by its point with one of the poles of a voltaic battery, have its lower rim immersed in a flat dish containing mercury, communicating by a wire from its centre with the opposite pole of the battery, radiating or converging currents will be established in the mercury, which, acting on the vertical currents existing in the sides of the cylinder, will cause it to revolve. If the currents tending to or from the cylinder be exterior to it, which may be obtained by surrounding the cylinder with a metallic ring of larger diameter, and making this ring the medium of communication with the battery, the revolution of the cylinder will be made in the opposite direction to what it was before.

§ 7. *Reciprocal Action of Circular Currents.*

(226.) The mutual actions exerted between two circular currents, may readily be collected from the application of the general law of attraction among those parts in which the directions of the currents are similar, and of repulsion where they are dissimilar. If one of the circles be fixed and the motion of the other be limited to revolution round an axis, the effects of their mutual action will depend on the position of the centre of the moveable circle with regard to the plane of the fixed circle, and also upon the position and inclination of the axis with relation to the line joining both centres.

(227.) If the centre of the moveable circle be in the same plane with the fixed circle, or not far removed from it, whatever be the inclination of the axis, a directive force will arise, tending to bring the whole of the circumference into that plane, and to make it assume such a position as that the currents in the adjacent portions of the circle shall be in the same directions. Thus C D, (*figs.* 135 and 136,) being the fixed,

Fig. 135.

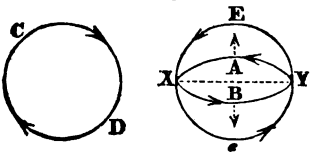
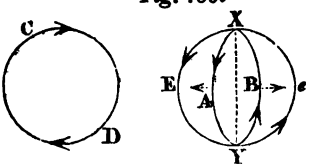


Fig. 136.

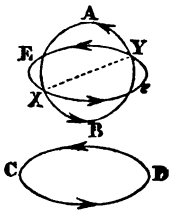


and A B the moveable circle, on the axis X Y, the directive force will bring the latter into the position E *e*, that is, in the same plane with C D; and this will happen equally, whether the axis be at right angles to the line joining their

centres, as in *fig.* 135, or coincide with it as in *fig.* 136, or have any other inclination to it.

228. If the centre of the moveable circle be any where in a line drawn through the centre of the former, and perpendicular to its plane, the moveable circle will tend to arrange itself in a plane parallel to the fixed circle, and having its currents moving in a similar direction. This is evident from *fig.* 137, in which the same letters as before are used to denote the corresponding points.

Fig. 137.



(229.) In both cases an approximative force takes place, whenever the moveable circle has arrived at its position of equilibrium; which force, in the latter case, is particularly strong, inasmuch as the attraction of the corresponding parts of the circles is uniform throughout the whole circumference.

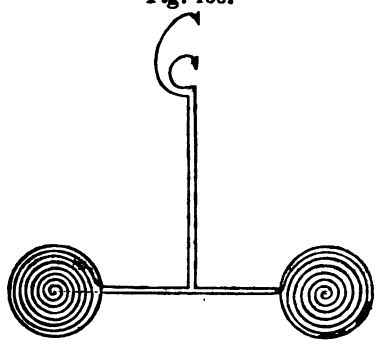
(230.) For each position of the centre of the moveable circle, intermediate to those above described, there exists a particular position of equilibrium, the line of which, if prolonged, would intersect the plane of the fixed circle at a certain distance beyond it.

(231.) All these positions of equilibrium are determinate, and exclude the possibility of any continued rotatory or revolving motions.

(232.) When an electric current, after traversing a certain line of conducting bodies, returns upon itself, so as to arrive at the point from which it had set out, or very near it, it has been denominated a *closed circuit*. Such is the case with the circles we have been considering. One of the most important facts on which the theory of electrodynamics rests, is that the mutual action of two closed circuits cannot produce, in either of these circuits, a continued rotatory motion in an invariable direction; and, consequently, no assemblage of closed circuits can ever be made to produce such rotatory motion, in whatever manner they may be disposed.

(233.) Experiments on the mutual actions of circular currents, either or each other or on straight conductors are most advantageously made by means of a flat spiral rendered *astatic*, by opposing to it a similar coil on the opposite arm of the lever, from the middle of which they are both suspended, as shown in *fig.* 138, the spiral turns being in

Fig. 138.



different directions in each, so that the rotatory influence of the earth on the one shall be exactly balanced by its influence on the other.

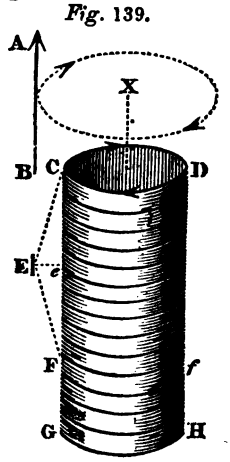
§ 8. *Mutual Action of Heliacal and Rectilinear Conductors.*

(234.) We have seen that the action of conducting wires rolled into the form of a flat spiral is similar almost in every respect to that of a simple circular wire; but when coiled round the surface of a cylinder, so as to constitute a helix, its action becomes much more complicated. When the extremities of the wire, after completing the helix, are made to return along the axis, as described in § 105, and shown in *fig.* 71, constituting what has been termed by Ampère an electro-dynamic cylinder, the whole may be considered as equivalent in effect to a succession of circles, whose planes are perpendicular to the axis, and occupy the whole length of the cylinder. In determining the forces that are called into operation by such an apparatus, we may, therefore, put out of consideration the slight obliquity which the turns of the spires have to the axis, and the effect of which is completely neutralized by the corresponding portion of the wire that passes along the axis; and we may regard the whole as composed of currents circulating at right angles to the length of the cylinder.

(235.) Since we have seen that the

influence of a single circular current C D, *fig.* 126, on a straight terminated current A B, perpendicular to the plane of the circle, is to induce in it a tendency to revolve with a motion parallel to itself, round the line drawn from the centre of the circle perpendicularly to its plane, it is evident that the addition of similar circles, placed in succession exactly below the first, (supposing the axis vertical, as in the figure,) will tend to increase this force of revolution. The effect of each additional circle, it is true, is less than the preceding, not only because its distance is greater, but also because its action is more oblique, and because the difference between the actions of the nearer and more remote portions of the circle continually diminishes as the angle between the lines drawn from the several points in the straight conductor, and the centres of the respective circles, increases, which is the case as they are further removed from the extremity of the straight conductor. From all these considerations, the force by which the current A B, *fig.* 139, is urged to revolve round the axis,

Fig. 139.



X, in consequence of the action of the lowermost circle G H, is plainly less than that exerted by the circle F *f*, and still less than that exerted by C D

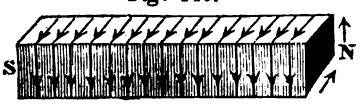
(236.) On the other hand, if we add in succession a number of circular currents *above* C D, they will conspire with the lower circles in their effect of producing a tendency to revolution in the straight conductor; but each will do this only by its action on that part of the conductor that is above its own plane; for its operation in any portion situated below that plane is to produce a revolution in the contrary direction. So that the action exerted upon any elementary portion of a vertical current, at E, for example, is, as far as it depends upon the circles above that which is nearest to it, exactly balanced by an equal number of circles below it; that is, the circles lying between C and *e* are counterbalanced by those lying between *e* and F, the whole of that portion of the cylinder between C and F being neutralized; and the only portion that is active being that which lies beyond F, that is, between F and G. This active part of the cylinder becomes smaller in proportion as the element is situated nearer to the plane which divides the cylinder into two equal parts; and at this point the action is reduced to nothing: on the contrary, it increases as the element comes nearer to either extremity of the cylinder, where it is the greatest of all. These extremities may accordingly be considered as the *active poles* of the cylinder, round which the revolution of the conductor is made: the resultant of all the forces called into action by every part of the cylinder has the direction of the tangent of the circle of revolution; that is to say, is at right angles to the line joining the straight conductor and the pole.

(237.) It is hardly necessary to remark that the action in this, as in every other instance, is reciprocal between the straight conductor and electro-dynamic cylinder; so that if the conductor be fixed and the cylinder moveable, the latter will revolve round the former; or, if restricted to a motion round its own axis, it will perform a rotatory movement round that axis.

(238.) The same tendency to revolution about the poles of an electro-dynamic cylinder, arising from a force of a tangential kind, apparently emanating from these poles, is observed to take place, whatever be the angle of inclination between the straight conductor and the axis of the cylinder. In order to explain this curious fact, the application of which is of considerable importance in a theoretical point of view, we must avail ourselves of the principle enunciated above (§ 198), namely, that the electro-dynamic action of currents that occupy in a similar manner two different surfaces, subtending the same angular extent, and lying in the same direction with reference to any point, on an elementary portion of current situated at

that point, are equal. It will also be convenient to analyze the actions of each circular current into those exerted in planes at right angles to each other, a mode of viewing them which, being analogous to the artifice of the resolution of forces constantly resorted to in dynamics, will make no difference in the results. Conceive, then, that the currents, instead of moving in the circumference of a circle, traverse the four sides of a square, and that the cylinder is represented by a square prism. S N, *fig.* 140, is intended to convey the idea of a prism, so constituted, the surface of which is

Fig. 140.

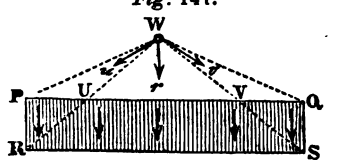


occupied by electric currents circulating round each of the laminæ, into which it may be divided by planes perpendicular to its axis, the direction of the currents being marked in the two sides which come into view, by the arrows. On the sides opposite to them, and which are not seen, the currents are, of course, moving in the contrary directions.

(239.) Let us now examine the effects of currents in each side upon a straight conductor, whose direction is at right angles to the axis, and which is placed in various positions with regard to the prism.

Let P Q R S, *fig.* 141, be the upper surface of this prism, its axis being horizontal; let W be the section of a vertical conducting wire, of indefinite

Fig. 141.



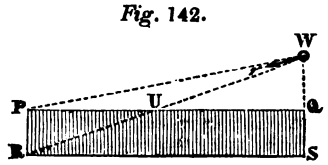
length, perpendicular to the plane of the figure; and let the current be moving in this wire in the same direction as those currents which traverse the adjacent vertical side of the prism, of which the upper edge is P Q. We shall suppose, for example, that the currents are ascending in the wire, and also in the side adjacent to it, whence they traverse the upper side from P Q towards R S (as denoted by the arrows), descending again on the side opposite to W, and of which the edge is R S, and returning on the lower side in a direction from R S towards P Q.

Since the currents are passing in opposite directions in the upper and lower surfaces of the prism, their effects on W (as far as any horizontal motion is concerned) are completely neutralized; and we need, therefore, only examine the actions of the vertical surfaces P Q and R S. Let R W and S W be the sections of two vertical planes, drawn from W to R and to S, cutting P Q in U and V respectively. It follows from the proposition above referred to that the actions of the currents in that portion of the surface P Q, adjacent to W, which is included between U and V, are exactly balanced by the currents in the whole of the surface R S, opposite to it, and which run in contrary directions. The resulting action, therefore, will be determined only by the currents in the remaining portions of the surface P Q, situated between P and U on the one side, and between V and Q on the other, both of which attract the current in W: the former in the direction of W *u*, the latter in the direction W *v*. These two forces combine in giving a resultant in the direction W *r*, indicating an attraction towards the centre of the prism.

(240.) In proportion as the situation of the vertical conductor is taken nearer to either of the extremities of the prism, such as Q S, for instance, the portion P U of the side P Q, intercepted between the plane R W and the extremity P, increases in extent, while the portion V Q diminishes. Consequently the forces arising from the attractions of the former portion are proportionally increased, and those from the latter diminished, and the resulting force gradually becomes more inclined towards P.

(241.) When W is situated in the plane of the side Q S, as in *fig.* 142, the force arising from the currents adjoining

Fig. 142.

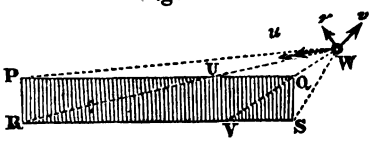


to Q vanishes entirely, and the action upon the wire depends solely upon the currents in the remoter division of the side P Q, namely, that comprehended between P and U. The resultant force will therefore be directed towards these

currents, being nearly at right angles to the line W Q.

(242.) When W is situated on the other side of this line, as shown in *fig.* 143, the extent of the active portion of the surface P Q has increased considerably, for it now occupies the large space P U; but its power has not increased in the same proportion, because

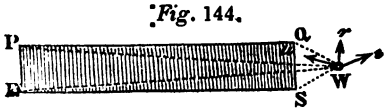
Fig. 143.



its action is more oblique, as well as more distant than it was before. The resultant of this action is in the direction W *u*. It is combined, however, with another set of forces, those arising from the uncompensated portion V S, of the surface R S, situated between S and the vertical plane W Q V. The currents in this portion are moving in a direction contrary to that in W: their action upon it is therefore repulsive, and the force thence arising may be represented by W *v*, which, combined with W *u*, gives, as a final resultant, the force W *r*.

(243.) When W is placed in the prolongation of the axis of the prism, as in *fig.* 144, it is attracted by the whole of the currents in the side P Q, and repelled by the whole of those in R S,

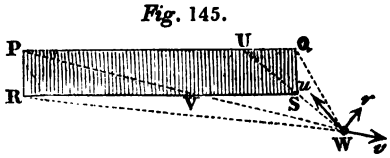
Fig. 144.



the former giving rise to the force W *u*, the latter to the force W *v*, their resultant being W *r*.

(244.) When W is in the situation represented in *fig.* 145, the currents situated between V and S are neutralized by those between P and U. Those

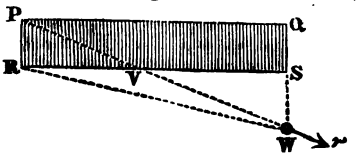
Fig. 145.



between R and V repel W in the direction of W *v*, while those between U and Q attract it in the direction W *u*, forces which produce the resultant W *r*.

(245.) When W is in the prolongation of the line Q S, *fig.* 146, the currents between P and Q being neutralized by

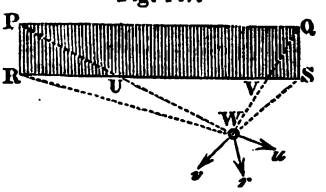
Fig. 146.



those between V and S, the only active currents are those between R and V, which being repulsive, the resultant is in the direction W *r*.

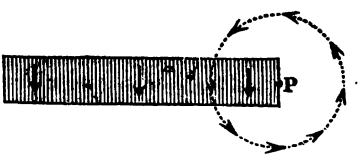
(246.) When the situation of W is as shown in *fig.* 147, the active portions of the currents are those occupying the spaces R U and V S, which being both repulsive, and acting according to the directions W *u* and W *v* respectively, join in producing the resultant W *r*.

Fig. 147.



(247.) Thus it appears that, combining all the results of this induction, the conducting wire is, in every situation, urged by a force impelling it in the direction of a tangent to the circumference of a circle, C, *fig.* 148, round the extremity of the prism, P, which may therefore be considered as having the functions of

Fig. 148.



a pole. The force thus arising possesses the same character of being rotatory and tangential as that which was exerted on the same wire when its direction was parallel to the axis: and if it possess this character in two directions that are at right angles to each other, it may fairly be inferred that the law is general, and that it applies to all the intermediate inclinations.

(248.) The explanation above given will be sufficient to convey a general idea of the application of the theory to

the phenomenon in question. But the subject has been investigated with all the rigour of mathematical analysis, and the results determined with all the precision that can be required for comparison with actual experiment. We have purposely omitted several of the minuter details which were even compatible with the popular view we have presented, but which would have required more complicated diagrams for their exposition, and considerably lengthened the inquiry, but which have no material influence on the ultimate conclusions. Thus, if the straight conductor, instead of being indefinite in length, were terminated, and wholly above the horizontal prism, it would be found that there is no longer that exact compensation between the currents in the upper and lower surfaces; for when the conductor is immediately above the prism, the upper currents have a much more considerable influence on it than the lower currents, and urge it on its revolution in the same direction as that in which it was moving from the effect of the other forces in operation. At the remotest part of the circle, the lower currents come more into operation from their acting with less obliquity than the upper currents, and concur, in their turn, in augmenting the tendency to revolution in the same direction.

(249.) The following laws are obtained as the results of the mathematical investigation of the subject:—

i. The action of a very slender electro-dynamic cylinder upon an elementary portion of a current may be resolved into two forces, acting in directions perpendicular to the direction of the current, and also respectively perpendicular to the lines drawn from it to each of the extremities of the axis of the cylinder; each of these forces being inversely as the squares of these distances.

ii. The action of an electro-dynamic cylinder upon an indefinite conductor, perpendicular to its axis, may, in like manner, be reduced to two tangential forces, as in the former case; but these forces are in the simple inverse ratio of the distances from the extremities of the cylinder.

iii. If the length of the electro-dynamic cylinder be supposed to be indefinite, its action upon an elementary portion of a current will depend entirely upon the relative positions of the element, and that extremity of the cylinder to which it is referred, and is influenced in no respect by the relative position of the axis of the cylinder.

iv. The action of this cylinder upon conductors, of whatever form or magnitude, is subject to the same conditions, being dependent solely upon the position of that extremity, which is referred to the conductor, and remains the same whatever be the direction of the axis of the cylinder *.

(250.) The conclusions thus deduced from the evidence of observation, combined with the deductions from theory, indicate the strongest analogy, and almost perfect identity, between the agency of electro-dynamic cylinders and that of magnets. The law of their action upon an electric current, and of the reaction of the latter upon both, is precisely the same; so much so, that if we had the command of sufficiently powerful currents, the electro-dynamic cylinder might be substituted for the magnet in all the experiments we have described in the last Chapter, and the same results, whether of attraction, repulsion, or revolution, would be obtained from them. The two extremities of an electro-dynamic cylinder exhibit all the properties possessed by the poles of a magnet: that end in which the current of positive electricity is moving in a direction similar to the movements of the hands of a watch, acting as the *south* pole of a common magnet; and the other end, in which the current is moving in a contrary manner, manifesting a *northern* polarity.

(251.) It will be readily anticipated, from the known resemblance between the action of electro-dynamical cylinders and of magnets on electric currents, that two such cylinders will act upon each other precisely in the same way as magnets do. Theory confirms the exactness of this general conclusion; for the following is the law to which mathematical examination conducts us, namely, that the mutual action of two electro-dynamic cylinders may always be represented by four forces, having the directions of lines drawn from each extremity of the one to both extremities of the other, and being to one another in the reciprocal ratio of the squares of these lines, provided these distances be not exceedingly small †.

* Ampère, Recueil d'Observations Electro-dynamiques, p. 343. See also Demonferrand's Manuel d'Electricité Dynamique; or Cumming's Translation, pp. 66, 67, 138, and 140.

† Ampère, Recueil d'Observations Electro-dynamiques, &c. p. 343.

(252.) The mutual action of electro-dynamic cylinders on magnets is the same as that of two magnets on each other, so that in any experiment the one may be substituted for the other without affecting the nature of the result.

Chapter XII.

Theories of Electro-Magnetism.

§ 1. *Electro-Magnetic Theory of Oersted.*

(253.) The discovery of the remarkable phenomena of electro-magnetism naturally gave rise to the invention of a variety of hypotheses for their explanation. Adopting the theory which ascribes the electric phenomena to the agency of two fluids, composing by their union a neutral fluid, and exhibiting their peculiar powers when that union is decomposed, and when they are obtained separately, Professor Oersted conceived that a distinct class of effects resulted during the act of their reunion; which was marked, not only by mechanical agitations among the particles of bodies, by the production of sound, by the evolution of light, and by the disengagement of heat, but also by the disturbance of the magnetic equilibrium. These phenomena seemed to indicate the occurrence of great and sudden changes taking place in the conditions of two powerful agents at the moment of their coalescence, and suggested to Oersted the idea that something analogous to a shock takes place when the fluids rush together from a distance. During galvanic action, the separation of the two electric fluids, proceeding without intermission in one part of the apparatus, and their reunion being in like manner effected in perpetual sequence along the conducting bodies which complete the circuit, he conceived that a continued series of electric shocks took place throughout the whole line of conductors; a condition which he expressed by the term *Electric Conflict.*

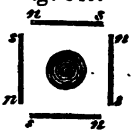
(254.) If these views be correct, it must follow that the electric fluids, which, whether at rest or in motion, have, when isolated, no apparent influence on magnetic bodies, acquire, during their conflict, the power of affecting these bodies. This hypothesis was expressed by Oersted in the following words: "The electric conflict acts only on the magnetic particles of matter. All non-magnetic bodies appear penetrable by the electric conflict, while magnetic bodies, or rather their magnetic particles, resist the passage of this conflict. Hence they can be moved by the impet s of the contending powers. It is sufficiently evident that the electric conflict is not confined to the conductor, but dispersed pretty widely in the circumjacent space.

"We may likewise collect that this conflict performs circles; for without this co dition, it seems impossible that one part of the uniting wire, when placed below the magnetic pole, should drive it towards the east, and when placed above it, towards the west—(see § 13, *figs.* 1 and 2): for it is the nature of a circle that the motions in opposite parts should have an opposite direction. Besides, a motion in circles, joined with a progressive motion, according to the length of the conductor, ought to form a conchoidal or spiral line; but this, unless I am mistaken, contributes nothing to explain the phenomena hitherto observed.

"All the effects of the north pole are easily understood by supposing that magnetic electricity moves in a spiral line bent towards the right, and propels the north pole, but does not act on the south pole. The effects on the south pole are explained in a similar manner, if we ascribe to positive electricity a contrary motion and power of acting on the south pole, but not upon the north*."

(255.) The views entertained by Oersted were very generally adopted by philosophers who prosecuted the path of discovery he had laid open. It was the prevailing belief that electricity in motion had magnetic properties, or rather that it imparted to the body that conducted it a species of transverse magnetism. Some conceived that the action resembled that of a series of magnets placed around the axis of the conductor, at right angles to each other, their poles being situated in four lines parallel to the axis, and forming a square, as represented in *fig.* 149, which

Fig. 149.



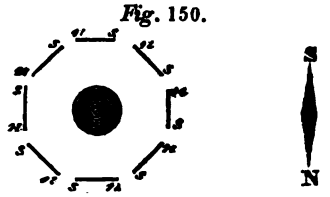
exhibits a section of the conducting wire, and four magnets with their poles

* Annals of Philosophy, vol. xvi. p. 276.

marked *n*, *s*, respectively, succeeding each other in a regular order of alternation round the wire. But this hypothesis cannot be a faithful representation of the phenomena; for it is found on experiment that the action of the conducting wire upon a magnetized needle is exactly the same in every part of its circumference. If the wire be vertical, for instance, its effect is the same in all azimuths, and has no relation to any rectangular planes passing through the axis of the wire.

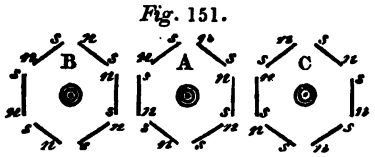
(256.) With this correction, the hypothesis that a conducting wire acts as if a series of minute magnets were placed in succession round its circumference, with their opposite poles facing each other, will account for a large class of phenomena. It explains why a compass needle assumes its peculiar position at right angles to the axis of the wire, in obedience to the directive influence of that particular portion of the imaginary series of magnets which is the nearest to the needle, see *fig.* 150; and also the mutual attraction between the needle

Fig. 150.



and the wire under these circumstances. It also explains the other fundamental fact in the science; namely, the mutual actions exerted between two conducting wires: for when the currents are passing in the same direction in both the wires as in A and B, *fig.* 151, the polarities

Fig. 151.



of the minute magnets on the sides adjacent to one another will be reversed, and they will consequently attract one another. The contrary will happen when the currents are passing in opposite directions in the two wires, as in A and C; for then the polarities of the magnets belonging to each, which are adjoining to each other, are the same in kind, and, therefore, repulsive of each other.

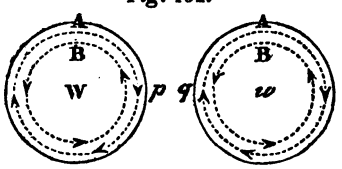
(257.) But there is still one class of phenomena which the hypothesis we are considering is totally inadequate to explain; that comprising the rotatory movements either of magnets or of conductors, and which movements may be maintained with uniform velocity notwithstanding the retardation from friction, or the impediments of a resisting medium; exhibiting, in fact, the extraordinary spectacle of a really perpetual motion. The supposition of a series of magnets encircling the conducting wire will not account for this continued motion; for it is certain that no actual combination of magnets, nor even any conceivable arrangement of magnetic particles, could ever, consistently with the known laws of magnetic action, produce any approach to perpetual rotation. In order to obtain such movements, the agent from which the force emanates must itself be in motion, and must revolve round the axis of the wire, while traversing it from end to end, with the utmost rapidity. Such was the peculiar kind of movement, partly longitudinal, and partly circular, which Dr. Wollaston attributed to the electro-magnetic agent, and which he termed its *vertiginous motion.*

(258.) A further emendation must, therefore, be made in the hypothesis in order to adapt it to the phenomena, by supposing that the two magnetic fluids, which accompany the electric fluids, when the latter are set in motion, and in a state of conflict, (if we choose to adopt the phraseology of Oersted,) acquire a *vertiginous motion* in opposite directions transversely to the axis of the conductor; that is, the boreal fluid revolving in one direction, and the austral fluid in the other; these determinations being given to them by the direction in which the electric fluids are moving in the conductor, dependent, of course, upon the relative positions of the poles of the voltaic apparatus from which they proceed. There will result from this peculiar kind of movement, not only all the effects that we have just seen to be the consequence of quiescent circles of magnets, but also those of a rotatory nature, which nothing but an agent in motion could produce. The tangential action of a conductor upon a magnet is a necessary consequence of the transverse motions of the magnetic fluids in the conductor; and the rotation of a magnetic pole round that conductor, or conversely, the revolutions of the con-

ductor round a magnet, are phenomena also naturally resulting from the vertiginous circulation of the two fluids.

(259.) The mutual attractions and repulsions of parallel conductors, are at once referred, as in the former case, to the action of parallel magnets having their poles in the same or in opposite directions. If, for example, the electro-magnetic current be moving in the same direction in two parallel conducting wires, the stream of austral magnetic fluid belonging to one wire will be flowing in the same direction as the boreal magnetic fluid belonging to the other wire, in that part which is adjacent to it; and, on the other hand, the direction of the boreal fluid of the former will coincide with that of the austral fluid of the latter wire, in the adjacent part. According to the known laws of magnetic action, attraction must be the result of such a state of things; for the boreal and austral fluids attract one another. If W and *w*, *fig.* 152, represent sections of the conducting wires in both of which the current of positive electricity is descending, the arrows in the circumference of the outer dotted circles

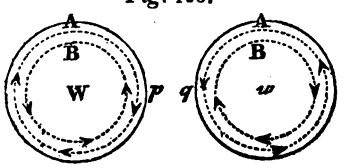
Fig. 152.



A A, will point out the directions in which the austral magnetic fluids circulate on the surface of the wires; and those on the inner circles B B, the directions in which the boreal fluids circulate, and it will be seen that in the parts *p* and *q*, when they are nearest to each other, the austral fluid in the one is moving in the same direction as the boreal fluid in the other, and we may, therefore, expect that they will attract each other.

(260.) If the electric currents be moving in contrary directions in the two wires, as represented in a similar manner in *fig.* 153, opposite effects will

Fig. 153.



result; for in that case both the streams of austral fluid are moving in the same direction in the adjacent parts of the wires, and must consequently repel one another; and the same thing happens with regard to the streams of boreal fluid, which flow in the contrary direction to those of the austral fluid.

(261.) Such, then, is the hypothesis that has been, after proper emendations, made to correspond with the phenomena, and which may be assumed as a correct representation of them. It must, at the same time, be admitted to be an exceedingly strained and artificial hypothesis, at variance with the analogy of all other physical forces, and repugnant to our ideas of that simplicity which seems to pervade all the operations of the material world. All other known accelerating forces, emanating from a certain point, and exerted upon another point, act in the direction of the line joining these two points. Such is the case with the electric and with the magnetic actions, in all the cases that belong exclusively to the one or the other of these two classes of phenomena. When two conducting wires, bent into helices, act upon one another, which they do in a manner that imitates very exactly the mutual action of two magnets, the action is purely electrical, and is exerted in the lines of direction that join the acting points. The same is the case with two magnets, when magnetism alone is concerned. But when a helix and a magnet act upon one another, and present the very same phenomena as in either of the preceding cases, the theory assigns a tangential direction to the forces then called into operation. That a mode of action which is simple and intelligible in the case of actions either purely electric or purely magnetic, should be so suddenly and so completely changed when the electric and magnetic fluids act mutually upon one another, would be a strange and scarcely conceivable anomaly in physical science.

(262.) We may avoid all these difficulties by adopting the theory of electro-magnetism devised by the genius of Ampère, and ably supported by his mathematical, in conjunction with his experimental researches. Of this theory we shall proceed to give an account.

§ 2. *Electro-Dynamic Theory of Ampère.*

(263.) The phenomena relating to the

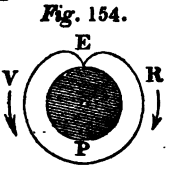
science of electro-magnetism may, as we have seen, be reduced to three classes, or general facts: the first being the evolution of a tangential and rotatory force usually exerted between a conducting body and a magnet; the second, the transverse induction of magnetism by the former in such bodies as are susceptible of receiving it; and the third, the attractive or repulsive force exerted between two electric currents traversing different conductors. In the magnetic theory already discussed, the first of these is considered as being the most general fact, and the other two as being merely its consequences. Ampère, on the contrary, assumes the last of these facts—that is, the mutual attractions and repulsions of electric currents, as the primary or fundamental fact, to which, by the help of a particular hypothesis as to the constitution of magnets, all the other facts, not only of electro-magnetism, but of magnetism also, are reducible.

(264.) His supposition is, that all bodies that possess magnetic properties, the globe of the earth being included among the number, derive those properties from currents of electricity continually circulating among the parts of which they are composed, and having, with relation to the axes of these bodies, one uniform direction of revolution, in planes perpendicular to those axes.

(265.) The striking resemblance which exists between the action of magnets, and that of electro-dynamic cylinders already described, and which extends through a wide range of phenomena, very naturally suggested the hypothesis on which this theory is founded; for since the circular currents in the latter are observed to produce effects similar to magnetic polarity, it is but an extension of the analogy to consider a magnet as deriving its properties from similar currents continually circulating in its substance.

(266.) In the account we have given of magnetism it will be seen that the phenomena attending the fracture of a magnet oblige us to consider magnetized iron as an aggregate of small particles of iron, each of which has the properties of a separate magnet (see MAGNETISM, § 141). In like manner, the hypothesis just stated, relative to the circulation of electric currents in the substance of a magnet, must receive a similar modification to that given to the theory of magnetism. Since the fragments detached from a magnetic bar are themselves complete magnets, the electric currents, from which it derives its properties, must be conceived as circulating round each of these fragments separately, or rather round particles smaller than any that can be obtained by mechanical division. Each particle, or magnetic element, may be regarded as constituting a voltaic circuit, analogous to a voltaic pile of which the two ends are united by conductors; the vitreous and the resinous electric fluids being separated at one point of the circuit, circulating in contrary directions round the particle, until they meet together, and by their reunion again forming the neutral fluid. The course of the fluids during this circulation is represented in *fig.* 154; V and R denoting respectively the paths of the vitreous and resinous electricities emanating from the point E in the particle of iron P, and flowing in the directions indicated

Fig. 154.

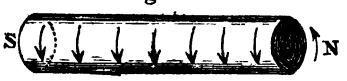


by the arrows, till they meet and coalesce on the opposite side. But as the effects of the one fluid are exactly the reverse of those of the other, the result is equivalent to the continued circulation of one of the fluids, the vitreous, for example, in one constant direction, E V P R.

(267.) A magnet, then, is to be considered as composed of an assemblage of parallel filaments, each of which is constituted by a series of particles, round which electric currents are circulating in the manner just described, all of them flowing in the same direction with reference to the axis of the filament, and moving in planes perpendicular to that axis. That extremity of the filament in which, when uppermost, the current of positive electricity is moving in a direction similar to that of the hands of a watch (the dial of which is also uppermost), has the properties of a south magnetic pole, and *vice versâ*. If the filament be placed horizontally, its north pole pointing to the north, then the currents on the western side are ascending, pass from west to east in the upper surface, descend on the eastern side, and return from east to west in the lower

part. This is shown in *fig.* 155, which represents one of these elementary magnetic filaments, the eastern side being presented to the spectator.

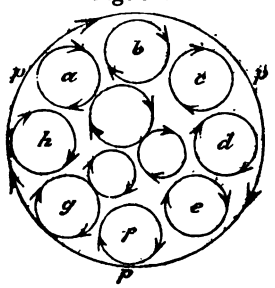
Fig. 155.



(268.) These currents which exist in each particle of a magnet, may therefore be considered as constituting closed circuits (see § 232), the effects of which on all bodies exterior to the circuit will depend on the difference between the actions of the nearest and the most remote parts of the circle described by the current. The united effects of a great number of these circular currents will almost entirely depend on those parts of the current which occupy the exterior surface of the mass.

(269.) Thus, supposing the magnet to be cylindrical in its shape, and its section shown in *fig.* 156, to consist of the sections of each of its component filaments *a*, *b*, *c*, *d*, &c., and round each of

Fig. 156.

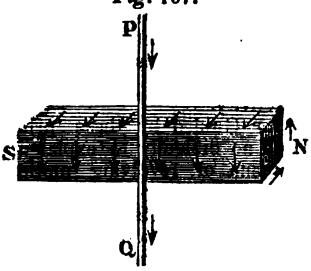


which electric currents are circulating in the directions indicated by the arrows, it is evident that the currents of all the interior parts will nearly, if not exactly, compensate one another, and that their action will be neutralized. But the currents that pass near the circumference are differently circumstanced, inasmuch as they are not compensated by any others; and their action is, therefore, fully exerted on the bodies that are near them, and is equivalent to that of a single circular current flowing uniformly round the circumference, *p*, *p*, *p*, of a circumscribing circle, in the same direction. Hence, in estimating the effects of the whole assemblage, we may confine our attention to that of a superficial current.

(270.) It is obvious that in order to institute an exact comparison between the action of a magnet, and that of an artificial assemblage of electric currents similar to that which is supposed by the theory to exist in the magnet, our imitation must be made by collecting together a great number of similar helices, in parallel directions, and uniting them in one mass. Such an arrangement is called by Ampère *an Electro-dynamic Solenoid**.

(271.) The tendencies which a magnet and conducting wire have to place themselves in positions at right angles to one another, was deduced from the electro-magnetic theory as a consequence of the supposed transverse situation of magnetic fluids resulting from the electric conflict—that is, accompanying the movements of the electric fluids. In Ampère's theory the transverse direction of the action is ascribed to the transverse movements of the electric currents in the magnet itself, which act upon the current in the conductor, and are also acted upon by that current, and tend constantly to establish a parallelism between them. Thus, since the currents in the magnet N S, *fig.* 157, move in planes perpendicular to the axis of the magnet, their action, being in those planes, is transverse to the axis, and tends to bring a straight conducting-

Fig. 157.



wire, P Q, into the transverse position represented in the figure, in which the direction of the current of the conductor is parallel to that of the current in the nearest part of the magnet. On the other hand, if the wire be fixed, and the magnet moveable, the forces will tend to bring the plane of that current, which occupies the middle of the magnet, into such a position as may include the straight conductor; and as the axis of the magnet is perpendicular to that plane, so also must it be at right angles

* Théorie des Phénomènes Electro-dynamiques, p. 95.

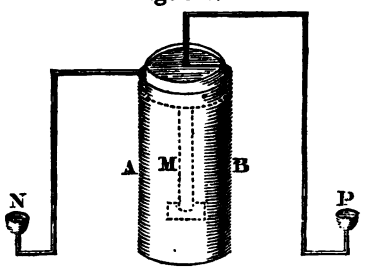
to the wire which acts upon it. When the magnet and wire have attained this relative position, it is evident that, since the adjacent currents move in the same direction in both, an attraction will take place between them. All this, as we have seen, is in perfect accordance with the observed phenomena.

(272.) It is unnecessary to pursue the application of this theory to the endless variety of cases of the mutual actions of magnets and conducting bodies, because, having already fully gone into the details of the explanation which is afforded of these facts by the principle of a tangential force emanating from both these agents, it will necessarily follow that they are all equally explicable on the electro-dynamic theory, if it be once proved that the basis of the former theory, namely the tangential force, is itself a direct consequence of the latter. Now this has already been established experimentally by the phenomena exhibited by the helices and electro-dynamic cylinders described in a former Chapter, § 107, and the same has also been deduced from theory, according to what was stated in § 249. It has been shown that the same tangential force results from the heliacal disposition of the current, whatever be the position of the axis of the helix relatively to the conductor on which it acts. We are warranted, therefore, in transferring this conclusion to the action of the circular currents assumed as existing in magnets, and as being the sole source of their activity.

(273.) Guided by these principles, we find no difficulty in explaining the phenomena of revolving motions so frequently resulting from the mutual actions of magnets and conducting wires; and which take place in exactly the same manner when helices or electro-dynamic cylinders are substituted for the magnets. It is instructive, however, to examine the particular cases we have already given in exemplification of the rotatory tendency arising from a tangential force, by applying to them the more general principles of electro-dynamic action. In many instances it will be found that the rotatory motions, although in part produced by the action of the currents in the magnet upon the current in the straight wire, are also in a still greater extent dependant on the influence of those portions of the current that traverse the mercury into which the conducting wires or the magnets are immersed.

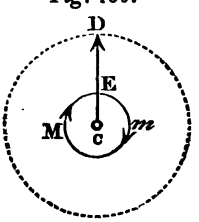
(274.) This is exemplified in the following arrangement represented in *fig.* 158, where the bent wire, proceeding

Fig. 158.



from the positive cup P, terminates in a steel point that is made to dip into the surface of a quantity of mercury contained in the vessel A B, in the centre of which a magnet, M, is kept floating in a perpendicular position by being loaded with a weight of platina at the lower end. A ring of copper is placed on the surface of the mercury, from the side of which proceeds a wire, which terminates in the cup N. The electric current, in passing from the steel point to the ring of copper, traverses the mercury, radiating from that point as from a centre, and consequently giving a revolving tendency to the currents in the magnet below them. The magnet, under these circumstances, revolves on its axis. A similar effect, but in a contrary direction, takes place when the course of the electric stream is reversed, and is made to traverse the mercury from the copper ring towards the steel point, producing converging instead of diverging currents. The explanation of these phenomena is obvious, from what has been said in § 203, 204. For let M in *fig.* 159, be one of the currents at the

Fig. 159.



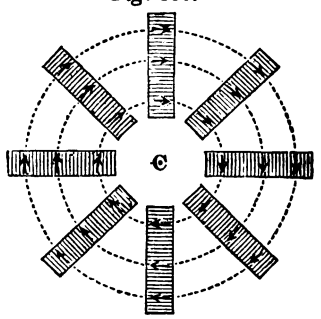
upper end of the magnet, and C D one of the diverging currents; the action of the portion E D will be to produce a revolving motion of the magnet in the

direction *m* E M, because the current in *m* is attracted, and that in M repelled by the current in E D.

(275.) If the point P were inserted, not, as before, in the centre of the fluid above the magnet, but to one side of it, the action of the currents would be more complicated, some being attractive and others repulsive, according to their situations relative to the magnet. The resultant force will be one at right angles to the line joining the centre of radiation with the axis of the magnet, and the effect of this force will be a motion of translation of the whole magnet; that is, of revolution round a line parallel to its axis, and exterior to its surface.

(276.) The presence of transverse currents in every part of the surfaces of magnets is well illustrated by their conjoined influence, when a number of magnets are placed horizontally, as in *fig.* 160, like the spokes of a wheel, with their similar poles turned towards the

Fig. 160.



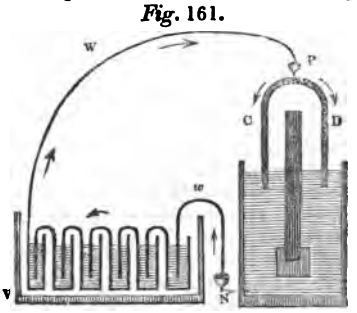
centre C. In this situation all the currents on the upper sides of the magnets are passing in the same direction with reference to the circumference of circles described from the centre C. They will therefore produce continued rotation in a vertical conductor, whose axis passes through that centre, but is terminated—that is, does not extend beyond that side of the plane in which the magnets are situated.

(277.) The theory of Ampère would lead to the conclusion that no mechanical arrangement of the parts of an electro-magnetic apparatus can give rise to rotatory movements, unless fluid conductors form some part of the voltaic circuit; and accordingly no attempt to obtain practically such movements has ever been successful.

(278.) It is, accordingly, impossible to obtain the revolution of a magnet round its own axis, either by the action of other magnets, or by that of an electric current, which traverses neither the magnet, nor a body that is so fixed to it as to move along with it. This is a direct consequence of the law derived from the electro-dynamic theory, that the mutual action of two closed circuits cannot produce in one of these circuits a continued rotatory motion in one constant direction; for it is evident that if this be true with regard to two single currents, it must also be true with regard to any assemblages of such closed currents, in whatever way they may be arranged. The utmost that can result is a tendency in one of them, if moveable, to assume a fixed position of equilibrium; if, therefore, the system be so constituted that it can only revolve round an axis, about which the circuits composing it are symmetrically arranged, it will acquire no motion whatever by the action either of a single closed circuit, or of an assemblage of such circuits. A magnet susceptible of no other motion than rotation round its axis is in this condition; and hence, if it derive its magnetic properties from electrical currents, it must be impossible to produce in it such a rotation by the action of other magnets.

(279.) On the other hand, a detached portion of a voltaic circuit moveable on an axis that coincides with that of a magnet may be set in motion, and made to revolve by the action of the closed currents, in the magnet itself. Thus let V *v*, *fig.* 161, represent a section of a voltaic pile, with its positive and nega-

Fig. 161.



tive wires, W, *w*, proceeding from its two poles, and inserted into the cups P and N respectively; the former being placed at the top of an arch of wire, of which the two branches descend on each side, and terminate under the surface of

a quantity of mercury, contained in the vessel, also seen in section; and the latter being at the end of a wire proceeding from the lower part of the vessel, and in contact with the mercury; while a magnet is made to float in an upright position in the axis of the vessel, by a weight of platina fixed to its lower end. The magnet, it will be seen, being unconnected with the wires, forms no part of the voltaic circuit, and remains unmoved by it; yet it excites movements in the conductors which surround its upper portion. For since, in the parts C and D, the currents of the wires are approaching those of the magnet, they will be impelled (see § 200) to turn round it in a direction opposite to that of the currents in the magnet: a reaction is at the same time exerted by the currents of the wires upon those of the magnets, which therefore tend to move the magnet *progressively*, or in the same direction as its own currents. (§ 203.) But the currents which pass from the lower ends of the wires through the mercury to the exterior of the vessel, recede from the magnet, and tend to impress on the mercury a motion of revolution in the direction of the magnetic currents; and, consequently, by the reaction of this force the magnet receives a tendency to revolve in the opposite direction. The two forces resulting from these contrary tendencies of the descending and the receding currents, oppose and partly destroy each other, as far as regards their effect on the magnet; and when the rotatory effects of the whole of the remaining part of the current composing the whole circuit, and including that of the pile itself, and its two wires, W and *w*, are taken into account, the compensation becomes complete, and the total effect reduced to nothing. Hence we see that, although the wires are made to revolve in one direction and the mercury in another, the magnet itself, being acted upon by equal and contrary rotatory forces, and unattached to any part of the circuit, remains perfectly unmoved.

(280.) But the case is altered if the magnet be so connected with the apparatus of the wires as to form a part of the circuit, even for a portion only of the current; for that portion of the current which thus passes through the magnet no longer exerts upon it any rotatory tendency, and may, therefore, be considered as suppressed: and since the action of this portion exactly counterbalanced the equal and opposite action of the remainder of the circuit, that equilibrium can no longer subsist, when this portion is removed, and the remainder of the current becoming effective, will produce a rotation of the magnet on its own axis. The direction of this rotation will be the same as that of the descending wires; hence the magnet may be connected with these wires, without altering the nature of the action, as in the experiment of Mr. Faraday, described in § 76.

(281.) It follows, also, from the principles of Ampère's theory, that when the moveable portion of the circuit which is attached to the magnet has both its extremities in the axis, no motion of this kind will take place; because no action can result between a system of closed currents and another current terminating at both extremities in the axis of the system.

(282.) The theory of Ampère implies a perfect identity in the mode of action of a magnet and of an electro-dynamic cylinder. A remarkable difference, however, has been observed between them. In the electro-dynamic cylinder the poles are situated at the very extremities of the cylinder; whereas, in ordinary magnets, they are always found to be nearer to the centre than the ends; the distance varying in different magnets. This circumstance was long considered as invalidating the truth of the theory *. It may, however, be explained consistently with the hypothesis, in two ways; either by supposing that the intensities of the currents gradually diminish from the middle to the extremities; or else by assuming that they acquire a degree of obliquity when at a distance from the centre of the magnet; that is, that they move in planes which are not exactly perpendicular to the axis of the magnet, but differently inclined in different parts. These effects are, indeed, not only quite consistent with Ampère's hypothesis, but follow as the natural consequences of the established laws of electro-dynamic action †.

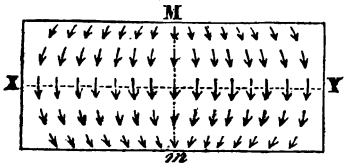
These positions of the different currents, according to their positions relative to the axis, will be best understood from *fig.* 162, which represents a longitudinal section of a magnet by a plane passing through the axis; the directions of the currents being marked by short

* This was urged as an objection by Mr. Faraday, in the Quarterly Journal of Science, vol. xii. p. 76.

† Ampère, Recueil, &c. pp. 257 and 340.

arrows. The elementary currents of those particles of the magnet which are situated in the axis, that is, along the line X Y, will, of course, on account of the symmetry of the figure, move in planes perpendicular to the axis; as also those in the medial plane M *m*,

Fig. 162.



passing through the centre of the magnet. But with regard to the currents nearer to the surface, they will, by the action of the interior currents, be turned towards the middle of the magnet, while those parts of the same currents that are nearest to the axis will be repelled from the middle towards the adjacent extremity; and the planes of their inclination will therefore be more or less inclined to the axis, as they are more or less remote either from the axis, and from the middle of the magnet, in the manner represented by the arrows in the figure. The total amount of inclination in the lateral currents will be greater in proportion to the intensity of the action of the interior currents, and also in proportion to their number; it will, therefore, be greater in proportion as the thickness of the magnet is greater compared with its length. We may conceive this relative thickness to be so excessive as that the forces tending to produce this inclination of the currents will at length overcome the coercive force, and prevent the development of magnetism. This consideration will easily explain the difficulty that is experienced in magnetizing a bar in such a manner as that the poles may be in the direction of the shorter diameter*; a remark which leads us to the subject of the induction of magnetism. Let us examine with what success the hypothesis of Ampère may be applied to this class of phenomena.

(283.) We have already seen that an electric current communicates magnetic properties by induction to such bodies in the vicinity as are susceptible of acquiring them. If these properties are owing to electric currents circulating in the particles of the magnetized body, or in the magnetic elements, as they have been called, (see Magnetism, § 154), there are two suppositions, either of which will account for this phenomenon. The first is, that electric currents, which did not before exist, are produced, or called into action, by the influence or another current in the vicinity. The second hypothesis is, that the electric currents pre-exist in all the particles of iron, or other bodies susceptible of magnetism previous to their acquiring this property, but without having any uniform direction; under these circumstances, their actions upon any external body counteract and balance one another, so as to constitute the neutral state. When, on the other hand, they are under the influence of an external electric current of sufficient power, they are all turned by it towards the same quarter, and assume a common direction; they will now co-operate in their action upon external bodies, and exhibit magnetic properties. This change is analogous to what takes place in the rays of ordinary light when, from being polarized in all possible directions, they become suddenly polarized in one particular direction.

(284.) It is implied in the first of these hypotheses, that every electric current tends to produce currents in a similar direction in other bodies. Ampère has proved, by the following curious experiment, that a powerful voltaic current possesses this power of exciting currents in neighbouring bodies that are not generally considered as susceptible of magnetism. A copper wire of considerable length, covered with silk thread, was rolled round a cylinder, so as to form a coil of some thickness. Within this coil, placed in a vertical position, a copper ring of smaller diameter was suspended by a fine silk thread, passing through a small glass tube, which was thrust between the threads of the copper coil. The circumference of the ring was thus brought, in every part, very near to the conducting coil, through which a very powerful voltaic current was sent. When a magnet was presented to the ring, under these circumstances, the latter was attracted or repelled in the same manner as if it had formed part of the same circuit as the coil. Hence it was inferred, that an electric current tends to induce in conductors, placed in its immediate vicinity, currents that move in similar directions.

* See Cumming's Translation of Demonferrand, Manual of Electro-Dynamics, p. 167 to 170, and also p. 250.

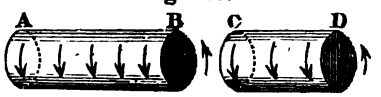
This tendency, indeed, is but feeble; and the first endeavours of Ampère to discover it failed, in consequence of his employing inadequate means; but, on repeating the experiment with more powerful batteries and magnets, he perfectly succeeded in rendering the action sensible.

It were much to be desired that this important experiment, upon the accuracy of which so much is made to depend in accounting for magnetic induction in Ampère's theory, were carefully repeated, and with every possible variation in its circumstances, so as to determine whether the effect which he observed is uniformly sustained, is invariably connected with its supposed cause, and is always proportioned to it; or whether it be not dependent upon some particular conditions in the current with relation to its tension, velocity, or intensity, or upon some temporary variation taking place in these conditions. In the particular form in which the experiment has been tried, it seems scarcely to warrant the very general conclusion which Ampère has deduced from it.

(285.) Even if we admit it to be established as a general fact, that electric currents, circulating in one body, are attended by similarly directed currents in neighbouring conductors, we are still not in a condition to decide the question, whether, in imparting magnetism to metals, there is an actual production of electric currents, or simply a change effected in the directions of currents previously existing in their particles. There is, however, no inconsistency in the supposition that the effect may be due to both these causes; for the action of an electric current may consist in giving a common direction to pre-existing currents, while it, at the same time, augments their intensity.

(286.) It is unnecessary to enter into long details as to the modes in which, according to the theory we are considering, an electric current, passing through conductors of different forms, whether straight, or bent into spirals, or helices, or a magnet, in which currents are supposed to circulate, induce magnetic polarity in the adjacent parts of pieces of iron or steel brought within the sphere of their influence, when we regard that polarity as consisting in the establishment of circular currents of the same description as those of the inducing magnet. It will be sufficient to show that the fundamental fact, namely, that either pole of a magnet tends to induce the opposite polarity in the adjacent end of a magnetizable body in its vicinity, is the direct and necessary consequence of the hypothesis. That this is the case will readily appear from considering that when the elementary magnetic filament A B, *fig.* 163, is brought near to a similar elementary filament, C D, in a neutral

Fig. 163.

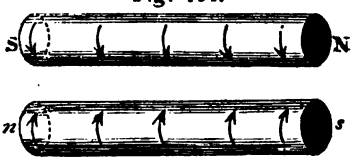


state, the currents which circulate in the former will excite in the latter a circulation of currents in the same direction, thereby rendering it magnetic. But since, according to the theory (§ 267), the kind of polarity manifested at either end of a magnet depends altogether upon the direction of the currents with respect to the axis at the extremity, it is evident that if the current at the end B revolves, as seen by a spectator looking at that end, in the direction of the hands of a watch on the dial, constituting the southern polarity, the current induced at the end of the other piece, C, revolving in the same direction in space, will appear to a spectator looking at that end to move in the contrary direction; it will therefore have a northern polarity, that is, one contrary to that of the adjacent end B, but similar to that of the remote end A. In like manner the polarity of D, if the inductive influence extend to that distance, will be the same as that of B; for the circumstances attending the revolution of its current are precisely the same in both.

(287.) When, on the other hand, the neutral bar is placed near and parallel to the inducing magnet, the action of the currents on the adjacent side of the latter will prevail over that of the currents on the remote side, on account of their greater proximity to the bar, and induce in its adjacent side currents running in the same direction; but these two sets of currents, being situated in different sides of their respective axes, will constitute magnetic currents in contrary directions, and, therefore, of opposite properties. Hence the poles of the induced magnet are reversed with relation to those of the inducing magnet. This will readily appear from an inspection of *fig.* 164. The same opposition of direction takes place when two parallel rollers turn upon one another, in con-

sequence of the parts in contact moving in the same direction.

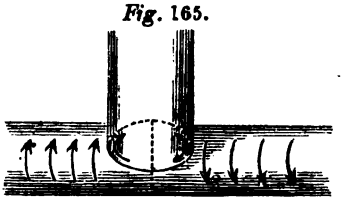
Fig. 164.



(288.) After the removal of the current which originally determined them, these induced currents continue to circulate with more or less permanence, according to the degree of coercive force inherent in the body. In soft iron they disappear almost immediately: in steel they continue to maintain themselves, and constitute permanent magnets. The action of heat is either to weaken or destroy the currents altogether, or else to derange the uniformity of their direction, so that they cease to act in concert, and the steel reverts to its neutral state. It is found, in conformity with the theory of Ampère, that all the effects of magnetic induction are produced equally well by electric currents circulating through spiral or heliacal conductors, as by artificial magnets.

(289.) The theory of Ampère furnishes a key to the explanation of a variety of facts attending the conversion of steel bars into magnets by the ordinary processes of magnetization, which are not intelligible on any other hypothesis. It accounts for the peculiar circumstances already noticed in the Treatise on Magnetism, regarding the relative advantages of the single or double touch, according to the inclinations given to the magnet when applied to the bar to be magnetized; and it more especially explains the frequent occurrence of consecutive points when certain methods are employed. Thus, let one of the poles of a magnet, the north, for instance, be placed on the middle of a steel bar, at right angles to it: see *fig.* 165. The form of the steel bar will, as

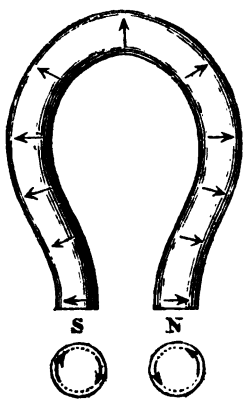
Fig. 165.



already remarked, give greater facility to the induction of currents in a direction transverse to its length; and the currents in the magnet running in this direction are those situated on the opposite sides of the magnet, supposed to be divided by the dotted line perpendicular to the length of the steel bar. But these portions of currents are themselves moving in contrary directions; the currents they respectively induce in the parts of the bar which they touch, and in the neighbouring parts, must therefore, in like manner, have opposite directions, giving rise to opposite polarities. Thus the two ends of the bar will be converted into north poles, while the point immediately under the centre of the magnet will be a consecutive point, or south pole.

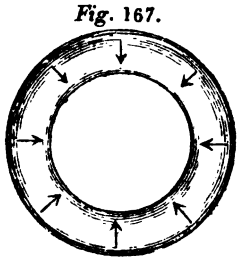
(290.) The phenomena attending the division or fracture of a magnet follow very naturally from the constitution assigned to it by Ampère's hypothesis; for, as the currents circulate in the same direction in the divided ends while they were united, they will appear to circulate in opposite directions with reference to the two sides of the plane which divides them, and which become the terminal planes of each fragment when separate. The polarities of the two ends must, therefore, be of opposite kinds; for the same reason that the adjoining ends, B and C, *fig.* 163, of two magnets placed in the same line, with their currents having similar directions, have opposite polarities. At the poles of a horseshoe magnet, the currents revolve in opposite directions with respect to the two ends of the bent axis; but the directions of the adjacent part of each current, as well as of the remote parts, are similar. See *fig.* 166.

Fig. 166.



(291.) If a steel bar, instead of being bent into the form of a horseshoe, be formed into a complete ring, *fig.* 167,

Fig. 167.



and then magnetized, it exhibits no magnetic properties as long as the ring is entire; but when broken into any number of portions, each part has two poles, and possesses all the properties of an ordinary magnet. This experiment suggested the theoretical investigation of the properties of a system of small circular currents situated in planes perpendicular to another circle, passing through all their centres. The result of the investigation of this problem led to a mathematical theorem exactly conformable to observation; a ring so constituted, or an *electro-dynamic ring*, as it has been called, being found, both from theory and experiment, to exert no action upon a voltaic conductor or magnet, at whatever distance from it, or in whatever situation it may be placed.

(292.) In viewing the application of Ampère's theory to the mutual action of two magnets, we might content ourselves with the observations already made as to the mutual action of two electro-dynamic cylinders, which may be taken as their representatives; and simply refer to the general principle deduced from theoretical considerations, § 251, namely, that the resultants of all the actions may be reduced to forces emanating from the poles, and inversely proportional to the squares of the distances. Yet as a more popular view of the actual operation of the forces derived from the attraction or repulsion of currents in the simpler cases may be more satisfactory, we shall examine a few of these cases.

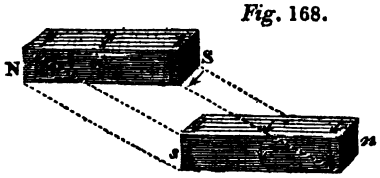
(293.) It will be evident that when two magnets are presented to each other, with their axes in the same line, it must depend upon the similarity or contrariety of the directions of the currents at the adjacent ends, whether these ends will attract or repel each other. The former, it is well known, happens when poles of opposite denomination front each other; the latter when similar poles are brought together. The motion of the currents in the first case may be aptly illustrated by two watches laid the one above the other, so that the dial of the one may be in contact with the back of the other, for the hands in both watches will then be moving in the same direction. We may obtain a representation of the second case, by placing the watches either face to face, or back to back; for in either of these situations, the motion of the hands in the two watches are in opposite directions. The electric currents in the former case will exert a mutual attraction; and in the last, a mutual repulsion.

(294.) In estimating the attractive or repulsive forces which arise in other relative positions of the magnets, we must take into account, not merely the terminal currents, but those which exist along the whole length of both magnets. The general resultants of all the forces thus arising may be reduced to attractive or repulsive forces between the whole of each of the sides of one magnet, and the whole of each of the sides of the other magnet. Thus, supposing two magnets to be situated horizontally nearly in the position to which they would be brought by the influence of terrestrial magnetism, the east side of the one will attract the east side of the other, and repel the west side; the west side will, in like manner, attract the west and repel the east. Hence the general tendency of all these actions is to turn the magnets so as to bring the two eastern sides, for example, as near together as possible, and parallel to each other; that is, into a relative position, such that the north pole of each magnet shall be adjoining to the south pole of the other; and in this situation the greatest amount of attractive force will be exerted.

(295.) In positions intermediate to these, and especially when much inclined to each other, the estimation of the resultant force in each individual case is often difficult, from the complex operation of the numerous forces that are in action in a variety of directions. Thus, if one of the magnets, situated as just described, parallel to each other, and with their dissimilar poles adjacent, be moved in the line of its axis till the two ends, having similar poles, are brought into the same plane, as shown in *fig.* 168, a strong repulsion

takes the place of the attraction before observed, notwithstanding the similarity of the currents in the two edges at S and *s* that are nearest each other. The reason is, that the attraction of the ad-

Fig. 168.



jacent sides is now much weakened both by the greater distances of their remoter portions at N and *n*, and also on account of the great obliquity of that action. The repulsions, on the contrary, exerted between the adjacent side of the one and the remote side of the other magnet, become very powerful, both from their increased proximity and more direct action; and they predominate accordingly. A similar account may be given of the attraction which takes place between dissimilar poles placed in a similar situation. The reasoning in both instances being analogous to what was stated (§ 236) with respect to the action of a helix upon an elementary portion of current placed in different situations with respect to the helix.

(296.) In the case of magnets that are not of a prismatic or cylindric shape, nor terminated by plane surfaces perpendicular to their axes, the estimation of the resultant force becomes much more complicated. All that we have now said on this subject, indeed, can only afford approximations to the solution of the problem of finding this resultant. The rigorous investigation of this problem would involve mathematical considerations of too great an extent for a treatise of this kind. The reader who may wish to prosecute the inquiry is referred more especially to the works of Ampère, in which the subject is treated with a masterly hand.

(297.) The magnetic influence of the earth being so perfectly analogous to that of other magnetic bodies, the theory of Ampère with respect to the constitution of such bodies must, if founded in truth, apply also to terrestrial magnetism, which must, according to that theory, be derived from electric currents circulating in the globe from east to west in planes parallel to the magnetic equator. The united effect of such currents would be to produce a southern polarity on the northern side of these planes, and a northern polarity on the southern side. It is scarcely necessary to point out how exactly the phenomena described in Chapter IX. (§ 128 to 147,) accord with the consequences of such an hypothesis. The magnetic axis of the earth, according to this view of the subject, is merely an imaginary line, perpendicular to the planes of the electric currents circulating in the earth, and passing through the centres of the circles described by those currents; and the directive power of the globe which acts on iron and on magnets on its surface, is the result, not of any real influence proceeding from those portions of the earth to which their poles point, but of the electro-dynamic action of currents circulating in the plane of the magnetic equator, in obedience to which the corresponding currents which circulate in the magnet place themselves, so as to approach to parallelism with the former; that is, to attain the position of equilibrium between the forces in operation. This position is that of a plane perpendicular to the line of magnetic direction, or the line of dip: and accordingly, since the currents in the magnet are themselves perpendicular to its axis, they will tend to bring that axis in that very line. Hence the phenomena of the dipping-needle, and hence the position assumed by the compass-needle, in the plane of the magnetic meridian, as being the nearest approach which its mode of suspension will allow it to make to the line of dip.

(298.) All the effects of terrestrial magnetism may be imitated by distributing wires round the surface of an artificial globe, so as to direct a galvanic current through them. Mr. Barlow, in a paper lately read at the Royal Society, describes the following experiment which he made with this view. A hollow wooden globe, sixteen inches in diameter, was furnished with copper wires passing in grooves along each parallel of latitude for every tenth degree. When an electric current was made to pass through these wires, in the same direction in each, it was found that a magnetic needle, properly neutralized with regard to the earth's action, and suspended in different situations near the surface of the artificial globe, arranged itself in positions perfectly analogous to those actually assumed by the dipping-needle in corresponding regions of the earth. It is probable that if we could indefinitely multiply these electric

currents on a globe so prepared, the apparatus might be made to represent with great accuracy every circumstance of magnetic dip and direction; and by employing, instead of a magnetic needle, an electro-dynamic cylinder, all the phenomena of terrestrial magnetism might be exhibited, without the intervention of magnetism, by means of electricity alone.

(299.) The origin of these electrical currents permeating the interior of the earth, and more especially its external layer, may possibly be traced to the action of the solar rays on successive parts of the torrid zone, which taking place from east to west, may excite currents of positive electricity in that direction, and in planes corresponding with the magnetic equator. The probability of such an effect being produced, and the inference from analogy that similar currents may be excited, and even exist permanently in iron and steel, is greatly increased by the recent discoveries of Professor Seebeck, that electric currents may be produced and maintained in circuits formed exclusively of solid conductors, by the partial application of heat. This discovery, which leads to a separate department of this science, to which the name of *Thermo-Electricity* has been given, will be treated of in the next Chapter.

(300.) A further confirmation of the electro-dynamic theory of magnetism is derived from its applicability to the curious phenomena of magnetic rotations, which have been described in the eighth chapter of the Treatise on Magnetism (§ 354 to 360). Soon after the discovery of this new class of facts, M. Arago suggested to M. Ampère the substitution of electro-dynamic cylinders for the magnetic bars in these experiments on the effects of rotation. The first trials made by these two philosophers in conjunction did not lead to any decisive result, in consequence of some defects in the apparatus they employed; but when these defects were obviated in the subsequent experiments which they made with M. Colladon, in which a very short double helix, forming a coil of about two inches in diameter, was used, they succeeded perfectly in obtaining the same results as if magnets had been employed*. Hence we may infer the complete identity between all the effects of a common magnet and an electro-dynamic cylinder.

(301.) We thus find that the theory of Ampère satisfies every condition that is required of a true theory, inasmuch as it affords a complete explanation of all the phenomena, even in their minutest details. It unites the character of simplicity in principle, and comprehensiveness in its applications; and by suggesting new combinations, it has led to the discovery of new facts. It also has an important advantage over the theory of tangential forces in presenting greater facility of mathematical investigation, and for the comparison of the analytical formulæ thence obtained, with the results of experiment; and thereby affording the most severe test of its accuracy. If the truth of the theory be established, it will effect an important step in the generalization of physical phenomena, by showing that all those formerly referred to the operation of an unknown principle, considered as distinct from electricity and denominated magnetism, are, in fact, essentially electric, and that the two principles are identical, and instead of being the bases of two separate departments of knowledge, are merely branches of a single and more extended and comprehensive science.

(302.) It must at the same time be acknowledged that much still remains to be done towards removing the difficulties opposed to this as well as other electro-magnetic theories, which are presented by the singular and apparently capricious phenomena of the induction of magnetism by electrical currents transmitted along conductors, and derived either from the voltaic or the common electrical batteries. We allude particularly to the results of the experiments of Savary, already noticed in § 164 to 168, and which have not yet been sufficiently generalized to admit of being explained on any hypothesis.

Chapter XIII.

Thermo-Electricity.

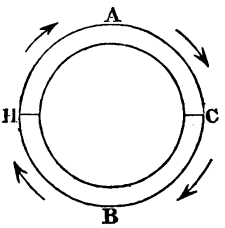
(303.) Professor Seebeck, of Berlin, discovered, in the year 1822, that currents of electricity might be produced by the partial application of heat to a circuit composed exclusively of solid conductors. The original experiment which established this fact was first announced in this country, in the Annals

* Ampère, Théorie des Phénomènes Electro-dynamiques, p. 196.

of Philosophy*. A bar of antimony, about eight inches long and half an inch square, was taken, and its extremities connected by twisting a piece of brass wire round them so as to form a loop, each end of the bar having several coils of the wire. On heating one of the extremities, for a short time, with a spirit-lamp, electro-magnetic effects were produced in every part of a circuit so formed.

(304.) Thus it appears that for constituting a circuit of this kind, two elements only are requisite; which may be represented in the diagram, *fig.* 169, by the conductors A and B, consisting

Fig. 169.



of two different metals, in contact in two points H and C, so that a circuit is formed in H A C B.

(305.) The electrical current thus excited has been termed *Thermo-electric*, in order to distinguish it from the common *galvanic current*, which, as it requires the intervention of a fluid element as one of its essential components, was denominated a *Hydro-electric current*. The term *Stereo-electric current* has also been applied to the former, in order to mark its being produced in systems formed of solid bodies alone. It is evident that if, as is supposed in the theory of Ampère, magnets owe their peculiar properties to the continual circulation of electric currents in their minute parts, these currents will come under the description of stereo-electric currents.

(306.) The chief evidence we possess of the existence of thermo-electric currents consists in the production of electro-magnetic effects. A compass-needle placed either within or without the circuit, and at a small distance from it, is deflected from its natural position in a direction conformable to its situation with regard to the circuit. Still stronger indications of electro-magnetic action are obtained by placing two ends of one of the metallic arcs in contact with the wires of a galvanometer. The thermo-electric current has also been found to excite contractions in the muscles of a frog: but as far as experiments have yet been tried, it is inadequate to effect chemical decompositions, the ignition of metals, or to exhibit sparks, or any other of the phenomena of ordinary electricity.

(307.) If the metallic arcs, through which a thermo-electric current is made to pass by the application of heat to one of the points of contact of the different metals, be delicately suspended, they will obey the action of a magnet brought near it. If the opposite poles of two magnets be placed on the outside of a circuit moving in a vertical plane, and turning on a vertical axis, the conductors may be made to revolve by continuing to apply the heat on the same side. Thus if the circular arrangement of bars represented in *fig.* 169 be suspended by a thread at A, and opposite magnetic poles be applied at H and C, out of the circle, while the flame of a spirit-lamp is held steadily at H, the combined actions of the two magnetic poles upon the adjoining ascending current at H, and descending current at C, will be to move the circle till its plane is at right angles to its former position. But the impulse it has acquired by the joint action of the magnets is sufficient to continue the motion until the side C arrives at the flame. This part of the circle being thus heated, while the part H is at the same time becoming cool, an electric current is now determined from C through A to H, and back again through B to C, which direction, with reference to the magnets, is the same as before, and the circle is urged onwards in its revolution. When it has completed an entire revolution, all the circumstances being the same as at first, another impulse will be given, and the circle will continue incessantly to revolve; the current moving alternately in opposite directions at every semi-revolution of the circle.

(308.) On the other hand, the pole of a magnet placed within the circuit will have no tendency to produce rotation; because the current in the opposite branches of the circle moves in contrary directions; and being, therefore, urged by the magnet to revolve in opposite directions, the circle will remain in equilibrium. But two systems of circles, supported each by a point on the ends

* New Series, vol. iv., p. 318.

of a horseshoe magnet, placed vertically, with the poles uppermost (that is, fixed as in *fig.* 50), and a lamp being placed half way between the poles, each of the circles will revolve by the action of that pole which is exterior to it.

(309.) It appears from these and other experiments of a similar kind*, that the mutual action of a magnet and a thermo-electric current is subject to the same laws as those of magnets and galvanic currents; and hence all the phenomena of the attraction, repulsion, or rotation of conductors conveying galvanic currents, may be exhibited by a thermo-electric current transmitted through the same conductors.

(310.) The two metals of which the combination and contact produce the most powerful thermo-electric currents, are antimony and bismuth, which we shall accordingly take as the representatives of their respective classes. As in the galvanic circuits, where the current of positive electricity is flowing directly from the copper to the zinc (see *Galvanism*, § 4), the latter is generally said to be positive with respect to the former (see *Galvanism*, § 73); so, in the thermo-electric circuit, the bismuth is generally said to be positive with regard to the antimony, because, in the colder portion of the circuit, the electric current is passing from the antimony to the bismuth†.

(311.) In the Treatise on Galvanism, we have given (§ 73) a list of metallic substances in the order of their oxidabilities, or rather in the order of their electrical relations, when united in galvanic circuits, with interposed acids. A number of experiments have been made by Professor Cumming, for the purpose of determining the comparative thermo-electric relations of the different metals by forming circuits of them taken in pairs. From these the following series has been deduced, descending from the extreme positive, as we have already defined it, which is bismuth, to the extreme negative, which is antimony.

Bismuth,	Cobalt, }
Mercury, }	Manganese, }
Nickel, }	Tin,
Platina,	Lead,
Palladium,	Brass,
Rhodium,	Charcoal, }
Gold,	Plumbago, }
Copper,	Iron,
Silver,	Arsenic,
Zinc,	Antimony.
Cadmium,	

(312.) In this series every metal is positive with respect to all those below it, and negative to those above. Hence any two metals occupying situations intermediate between the two extremes will together compose a thermo-electric circuit similar to, though of less power than that formed by bismuth and antimony.

(313.) The order in which the metals stand in the above series does not continue the same at all temperatures: thus gold, silver, copper, brass, and zinc, should be placed below iron in high temperatures, though they rank above it in a low heat.

(314.) On comparing the series above given, which represents the thermo-electric relations of the metals, with that given in the Treatise on *Galvanism*, § 73, which represents their galvanic relations, it will be evident that there is no correspondence between them.

(315.) The contact of the metals in these experiments is most completely secured by soldering them together; but in most cases it will be sufficient, if they are in the form of wires, to twist them closely together. Mercury may be conveniently employed as the intermedium between other metals: the mercury being previously heated, the extremities of each piece composing the pair being dipped into it at the same moment, and the other extremities being applied to a galvanometer. Even a small fragment of any metallic substance is sufficient to afford indications of its thermo-electric relations, if placed upon a disc of the metal with which it is to be compared, and touched with a hot wire; the circuit being completed through the wire and the disc. But it is found that the results of experiments so made do not always accord with those obtained by employing larger pieces, for it appears that the effect is much influenced by the relative dimensions of the heated surfaces. Even when the experiment is made by plunging the metals to be examined in heated mercury, the direction of the current will be determined, in many cases, by the order in which they have been immersed.

(316.) Considerable diversities take

* For a more detailed account of these, see Cumming's Manual, already quoted.

† There is still some confusion in the application of the terms positive and negative to the different parts of the circuit, by different authors, and sometimes even by the same author in different places.

place in the directions of the current when the metals contain any alloy, or are not in a state of perfect purity. Thus, although bismuth and tin are each positive with regard to copper, yet an alloy of the two former is found to be negative with regard to the latter metal.

(317.) We are yet far from possessing any theory by which the whole of the facts belonging to *thermo-electricity* can be satisfactorily explained. The most intelligible account of them appears to be that given by Becquerel*, which proceeds upon the hypothesis, that whenever a particle of a metal receives heat from a body of a higher temperature than itself, part of the neutral electric fluid which is attached to it is decomposed, the vitreous fluid being retained, and the resinous fluid driven off, and passing into the adjoining particles of metal. In proportion as the heat extends, by communication from particle to particle, similar effects take place in each of those that are acquiring heat, while contrary effects are taking place in all those that are losing heat. Thus, the simple diffusion of that portion of heat which was originally received by the first particle, produces only an oscillatory movement of the electrical fluids between adjacent particles, attended by a series of decompositions and combinations of the two electric fluids. But if the source of heat be permanent, so that the temperature of the first particles which receive it be uniformly maintained, the retrograde movements of the decomposed electric fluids are prevented, and a continued current of each takes place in opposite directions; the negative electricity being impelled forwards from the parts where the temperature continues high to those which continue to be colder, and a positive current moving in the contrary direction. It follows, from this hypothesis, that when two different metals are placed in contact, so as to constitute a circuit, the currents from the heated parts that are conjoined will be urged in opposite directions; but the strongest will prevail, and the thermo-electric current actually observed is that which results, and of which the intensity is equal to the difference between the two that are simultaneously developed.

(318.) Thermo-electricity does not appear to have its source in any chemical changes taking place in the materials composing the circuit. Oxidation, at least, has no share in the effect; for Becquerel has repeated the experiments of Seebeck and others, relating to this mode of action, when the apparatus was surrounded by hydrogen gas, without any sensible difference in the results.*

(319.) The great peculiarity which distinguishes thermo-electric currents from those produced by galvanic action, is that the *quantity* of circulating electricity is much greater compared with its *intensity*. They are, in this respect, still further removed from the condition of streams of electricity produced in the common electrical machine, which possess a much greater intensity, though they are much less considerable in quantity than galvanic currents. Hence it is chiefly by their effects in producing deviations in the magnetic needle that the existence of thermo-electric currents is recognised. The low state of intensity of these latter currents occasions great loss of power whenever they have to traverse any considerable line of conductors,—even of metals, which are the most perfect conductors. On this account it is that very little advantage is gained by forming compound circuits; that is, arranging their elements in a series of alternations analogous to those of the voltaic pile. Messrs. Fourier and Oersted made trials of this kind; first combining three bars of bismuth with three bars of antimony, placed alternately, so as to form the sides of a hexagon, and with their contiguous ends soldered together, thus composing a thermo-electric circuit, which included three pair of elements. The length of the bars was about four inches and a half, their breadth about half an inch, and their thickness one-sixth of an inch. This circuit was placed upon two supports, and in a horizontal position, one of the sides of the hexagon being in the magnetic meridian. A compass-needle was placed below this side, and as near to it as possible, and was very sensibly affected when one of the solderings at the junctions of the bars was heated with the flame of a lamp. The deviation was considerably increased on heating two of the alternate angles of the hexagon; and a still greater deviation was produced when the heat was applied to the three alternate angles. Similar effects were produced when, instead of

* See Annales de Chimie, tome xli. p. 353.

* Annales de Chimie, tome xli, p. 359.

applying heat, the temperature of one or more of the other angles of the hexagon was reduced by means of ice. When the action of the ice was combined with that of the flame, applied at the same time to the alternate angles all round the hexagon, the effect was still more considerable, the deviation of the needle amounting to sixty degrees.

(320.) By continuing these experiments with more numerous alternations, it was found that the total effect of a compound thermo-electric circuit is very inferior to the sum of the effects which the same elements could produce when employed in the formation of simple circuits, so that the electro-magnetic forces called into action increase in a much less ratio than the number of alternations constituting the series *.

(321.) The latest thermo-electric experiments are those of Messrs. Nobili and Melloni, of which an account was read to the French Academy of Sciences in September last (1831.)† A thermo-electric pile, consisting of thirty-six pairs of plates of bismuth and antimony, having a galvanometer with two needles attached to it, was found to be so sensible as to be affected by the warmth of a person at the distance of thirty feet. A number of delicate experiments were made with this apparatus on the permeability of bodies to radiant heat, on the temperature of insects, and on the powers of different bodies of emitting, reflecting, and absorbing heat. Considerable doubt is also thrown by these inquirers on the conclusions of Fourier and Oersted with respect to the limited effect of increasing the number of alternations in augmenting the intensity of the current.

(322.) It would appear also, from the observations of Professor Cumming, that although the hydro-electric and thermo-electric currents may both be regarded as continuous, when compared with those of common electricity, excited by the electrical machine, which are manifestly discontinuous (see *Galvanism*, § 21 and 94), yet when the hydro-electric and thermo-electric currents are compared with one another, the continuity of the latter is by far the most complete. This will appear evident from the consideration that, as it is necessary that one of the three elements of a galvanic circuit must be a fluid (see *Galvanism*, § 69), it will, therefore, be a more imperfect conductor than the metals, and will oppose some degree of resistance to the passage of the electric currents circulating through the whole assemblage.

(323.) There are, therefore, strictly speaking, three states of electricity. That derived from the common electrical machine is in the highest state of tension, and accumulates till it is able to force a passage through the air, which is a perfect non-conductor. In the galvanic apparatus the currents have a smaller degree of tension; because, although they pass freely through the metallic elements, they meet with some impediment in traversing the fluid conductor. But in the thermo-electric currents the tension is reduced to nothing, because throughout the whole course of the circuit no impediment exists to its free and uniform circulation.

(324.) These considerations serve also to explain why the latter species of current is inadequate to effect any kind of chemical decomposition, or even to produce any degree of permanent magnetism. It has hitherto been found impossible to magnetize steel bars by means of thermo-electricity, although the apparatus employed for that purpose was capable of producing a strong effect on the magnetic needle.

(325.) It is probably owing to some quality of this kind in the currents, which theory assigns as the source of magnetism (namely, from deficiency in tension), that all the endeavours which have so many different times been made by various experimentalists to obtain from magnetism any effects that may be considered as exclusively electrical, have uniformly failed. Although a magnet is powerfully affected by a current of electricity proceeding from a voltaic battery, it does not appear that the magnet is capable of augmenting or diminishing either the intensity or velocity, or any other of the qualities of the electric current. The only way in which the reaction of the magnet is shown, is by giving the electric current a tendency to lateral deflexion, as if urged by tangential forces proceeding from the poles of the magnet. If the wire of a galvanometer form part of the voltaic circuit, and a powerful magnet be applied to other parts of the circuit, whether bent into a helix or not, no indication of any action from the magnet is afforded by the needle of the galvano-

* Quarterly Journal of Science, xvi. 126.
† Bulletin des Sciences, No. II. for 1831.

meter.* We understand, however, that Mr. Faraday is at present engaged in an experimental inquiry upon this subject, which cannot fail, in such able hands, to lead to important results.

Chapter XIV.

Influence of Light on Magnetism.

(326.) Professor Morichini of Rome announced, in the year 1813, his having discovered that steel, exposed in a particular manner to the concentrated violet rays of the solar spectrum, became magnetic; but the uniform failure of the experiment, when tried by every other person, had created great doubt of the accuracy of the result as reported by Morichini. In the course of some experiments made by Mr. Christie, in the year 1824, he was led to the conclusion that the solar rays actually do exert a sensible influence on magnetism, which is shown by their affecting the vibrations of a magnetized needle exposed to them, quite independently of the effects produced by the heat which they impart. A needle, six inches long, contained in a brass compass box with a glass cover, was suspended by a fine hair, and made to vibrate, alternately shaded and exposed to the sun. He found, from a number of trials, that the vibrations of the needle, when exposed to the sun, ceased in a much shorter time than when they took place in the shade. That this greater slowness of the vibrations was not attributable to an increase of temperature, was proved by the needle's being observed to vibrate more rapidly when its temperature was raised by other means†.

(327.) In the summer of 1825, Mrs. Somerville was induced, by the unusual clearness of the weather, to investigate this subject‡. Having at that time no information of the manner in which Morichini's experiments had been conducted, it occurred to her that if the whole needle were equally exposed to the violet rays, it was not probable that the same influence which produced a south pole at one end, would, at the same time, produce a north pole at the other. She therefore covered half of a slender sewing-needle, an inch long, with paper, and fixed it in such a manner as to expose the uncovered part to the violet rays of a spectrum thrown by an equiangular prism of flint glass, on a pannel at five feet distance. As the place of the spectrum shifted by the motion of the sun, the needle was moved so as to keep the exposed part constantly in the violet ray. The sun being bright, in less than two hours the needle, which before the experiment showed no signs of polarity, had become magnetic, the exposed end having the properties of a north pole.

The season continuing favourable, afforded daily opportunities of repeating and varying the experiments with needles of different sizes, and placed in different positions with respect to the meridian, and at different distances from the prism. The results were nearly uniform, and similar to that above stated. It was not found necessary to darken the room, provided the spectrum was thrown out of the direct solar rays.

(328.) Mrs. Somerville next endeavoured to ascertain whether the other prismatic rays had the same property as the violet. Needles, previously ascertained to be unmagnetic, exposed to the blue and green rays, sometimes acquired magnetism, though less uniformly and less quickly than in the violet ray: when magnetism was thus communicated, it seemed to be equally strong as in the former case. The indigo ray succeeded nearly as well as the violet. The exposed end, in almost every case, became a north pole. In no one instance was magnetism produced by the yellow, orange, or red rays, though in some instances the same needles were exposed to their influence for three successive days; neither did the calorific rays of the spectrum produce any sensible effect.

(329.) Pieces of clock and watch spring were next tried with similar success, and were found to be even more susceptible of this peculiar magnetic influence than needles, possibly on account of their blue colour, or greater proportional surfaces. The violet rays concentrated by a lens produced magnetism in a shorter time than the prism alone.

(330.) Experiments were next instituted by transmitting the solar rays through coloured media. Needles, half covered with paper, were exposed on a stone outside a window, under a blue glass coloured by cobalt, to a hot sun for three or four hours. They were found to be feebly magnetic; but their

* See Quarterly Journal of Science, xix. 338.
† Philosophical Transactions for 1826, p. 219.
‡ Ibid. p. 132.

magnetism was not permanently retained. In subsequent experiments, by an exposure of needles under the same circumstances, for six hours, a very sensible degree of magnetism was acquired, and remained permanent. The rays transmitted through the blue glass employed in this experiment blackened muriate of silver as powerfully as those transmitted through uncoloured glass; thus proving that it was freely permeable to the chemical rays of the solar spectrum. Green glass was also tried; and the rays which had penetrated it were likewise found to communicate magnetism. The white light of the sun produced no magnetic effect whatever on needles exposed to its influence.

(331.) Although the experiments, of which we have just stated the results, are minutely detailed in the paper above referred to in the Philosophical Transactions, yet, in many trials made by other experimentalists, no success has been obtained. The experiments on the oscillations of the needle were repeated by Messrs. P. Riess and L. Moser without any satisfactory result*. We may, therefore, consider the subject as still open to inquiry, and as requiring a more minute and scrupulous investigation.

Chapter XV.

Origin of Terrestrial Magnetism.

(332.) Several causes have been assigned for the magnetic influence which the globe of the earth is found to exercise, not only over the magnetic needle, but also, as we have seen, over currents of voltaic electricity transmitted through conductors. (*See* Chapter IX. § 128, *et seq.*) Among the various substances which occupy the interior of the globe it is extremely probable that chemical actions of different kinds are incessantly occurring. These actions will, for the most part, however, be very slow, and will continue with a certain degree of uniformity for very extended periods of time. They will occur more especially in the superficial strata of the earth, where the combined agencies of water, of atmospheric air, and of heat are in constant operation. The influence of the solar rays on a surface of such vast extent must be very considerable: and excepting in the vicinity of the poles, every portion of that surface is exposed in succession to their action, and acquires during that exposure a certain degree of heat; which heat is again lost by nocturnal radiation. Although the effect of these alternate changes of temperature may extend only to a small depth below the surface, yet considering their immense superficial extent, they may be sufficient to give rise to thermo-electric currents of considerable power. It has been conjectured, also, that these effects may be combined with an influence of another kind, more directly derived from the rotation of the earth on its axis, on the principle that all bodies have been found to exhibit magnetic polarity by rotation.†

(333.) That electric currents do really circulate in different parts of the solid strata of the earth, is not merely matter of conjecture: the existence of such currents has been lately proved, in the most satisfactory manner, by Mr. Robert Fox, in a paper "On the Electro-magnetic properties of metalliferous veins," which has been recently published in the Philosophical Transactions*. Having been led from theory to entertain the belief that a connexion exists between electric action in the interior of the earth, and the arrangement of metalliferous veins, he was anxious to verify this opinion by experiment. The first trials he made with this view were unsuccessful: but by persevering in his attempts, he soon obtained decisive evidence of considerable electrical action in the mine of Huel Jewel, in Cornwall. His apparatus consisted of small plates of sheet copper, which were fixed in contact with ore in the viens by copper nails, or else wedged closely against them by wooden props stretched across the galleries of the mine. Between two of these plates, at different stations, a communication was made by means of copper wire, one twentieth of an inch in diameter, which included a galvanometer in its circuit. In some instances three hundred fathoms of copper wire were employed.

(334.) The intensity of the electric currents was found to differ considerably in different places. It was generally greater in proportion to the greater abundance of copper ore in the veins, and in some degree also to the depth of the station. This curious fact may possibly afford the miner some useful indications as to the relative quantities of ore which the vein contains, and also as

Annales de Chimie, xlii. 304.

* Cumming's Manual, &c. p. 231.

† For 1830, page 399.

to the directions in which it is most productive. The electricity thus perpetually in action does not appear to be in any respect influenced by the presence of the workmen and their candles; nor even by the explosions of gunpowder in blasting.

(335.) Mr. Fox observes that ores which transmit electricity have generally some conducting material interposed in the veins between them and the surface: a structure which appears to bear some analogy to the ordinary galvanic combinations. These electrical currents which pervade mines were found to have various and frequently opposite directions in different parts of the same mine.

(336.) The metals are probably not the only substances capable of giving rise to electrical currents in the earth; for it is well known that galvanic combinations may be formed by arrangements of elements that are not metallic. (*See* Galvanism, § 87.) The direction of each current will of course be determined by the relative positions of the elements from which it is derived; but even if we suppose the arrangement of these elements to be fortuitous, a prevailing current will still result, arising from the difference of their actions; for it is infinitely improbable that, without a designed arrangement, the currents in opposite directions should be exactly equal, so as to destroy one another. Irregularities of distribution probably exist with regard to the materials composing the interior of the globe; the resultant electro-magnetic action of the whole combination being that of which we witness the effects, and which may be considered as due to electrical currents circulating in directions parallel to the magnetic equator round the surface of the earth.

(337.) Even in the irregularities incident to the magnetic forces derived from the earth we may discern the operation of causes which are periodical in their operation. Thus the diurnal and annual changes of the variation of the needle may be traced to corresponding changes in the position of the different parts of the earth with regard to the sun, in as far as these electric currents are dependent upon solar influence. The progressive changes in the variation, which embrace longer periods of time, are less easily accounted for, and appear referable to causes which act at greater depths below the surface of the earth; and are probably connected with chemical changes taking place in the interior of the globe, of which we can possess no certain knowledge.

(338.) On the whole, then, it must be allowed, that there are strong grounds for the belief that there subsists some mutual connexion, or rather an intimate relation and affinity, between the several imponderable agents, namely, *Heat*, *Light*, *Electricity*, and *Magnetism*, which pervade in so mysterious a manner all the realms of space, and which exert so powerful an influence over all the phenomena of the universe.

Note. Since the above was sent to the press, a paper, by Mr. Faraday, has been communicated to the Royal Society, disclosing a most important principle in electro-magnetism, of which, I regret, I can only give the following brief statement.

By a numerous series of experiments, Mr. Faraday has established the general fact, that when a piece of metal is moved in any given direction, either in front of a single magnetic pole, or between the opposite poles of a horse-shoe magnet, electrical currents are developed in the metal, which pass in a direction at right angles to that of its own motion. The application of this principle affords a complete and satisfactory explanation of the phenomena observed by Arago, Herschel, Babbage, and others, where magnetic action appears to be developed by mere rotatory motion, and which have been erroneously ascribed to simple magnetic induction, and to the time supposed to be required for the progress of that induction. The electro-magnetic effect of the elective current induced in a conductor by a magnetic pole, in consequence of their relative motion, is such as tends continually to diminish that relative motion; that is, to bring the moving bodies into a state of relative rest: so that, if the one be made to revolve by an extraneous force, the other will tend to revolve with it, in the same direction, and with the same velocity.

POSTSCRIPT.

THE design of the last four Treatises has been to offer a condensed and methodical work on that important department of Natural Philosophy which comprises the diversified phenomena of Electricity and Magnetism. These phenomena, which were formerly regarded as the effects of two perfectly distinct agents, are now discovered to have an intimate relation to one another, and, in all probability, to be dependent on one and the same principle: in like manner, as it was found by Newton that the simpler mechanical phenomena of the universe are the results of the single principle of gravitation. A succinct and connected account of the numerous discoveries which the exertions of philosophers have recently brought to light on this highly interesting branch of physical science, collected from the various scientific journals and transactions through which they are dispersed, and digested in a didactic order, seemed to be particularly wanting, and to be especially calculated to further the objects of the *Society for the Diffusion of Useful Knowledge*. In pursuance of this design, I have aimed at giving to the subjects treated as much condensation as was compatible with perspicuity. I have endeavoured to conduct the student, by a regular progression, from the simpler to the more complex topics of research; and I have also been anxious, by placing constantly before his view the distinction which exists between ascertained facts, and the hypotheses and theories devised for their explanation, to illustrate the precepts of Bacon by examples, and to foster that genuine spirit of philosophical inquiry by which alone error can be avoided, and truth attained.

For the many deficiencies which I fear the reader will discover in the completion of this design, I have to plead, in extenuation, the very scanty portion of leisure, which the continual pressure of my professional duties leaves at my disposal. When I undertook this task, at the request of the Society, above four years ago, I was far from anticipating the extent of the labour it has imposed upon me; and from the multiplied interruptions to which I have been subject, I have been compelled to prosecute the work in a desultory manner, and at irregular and uncertain intervals.

Since the publication of the earlier Treatises, many valuable researches have been made, both in Electricity and in Galvanism, which deserve to be recorded in their proper places. This, however, is an inconvenience which, in the present age of improvement, must be incident to every scientific Treatise; for while so many accessions are daily accruing to the stock of information, it is hardly possible to keep pace with the rapid growth of knowledge; nor can we ever hope to incorporate the whole of the discoveries, which have been made up to the last moment of publication, in a systematic work on any science. To wait till perfection is attained would be vain and fruitless presumption; for the architecture of science has this peculiarity, that the foundations must be prepared, and the superstructure begun, long before the plans and elevations are completed. To posterity will be left the task of adding the key-stone, and of removing the scaffolding which interrupts the symmetry of the perfect edifice.

P. M. ROGET.

39, *Bernard-Street, Russell-Square,*
December 12th, 1831.

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TO THE

TREATISES ON ELECTRICITY, GALVANISM, MAGNETISM, AND ELECTRO-MAGNETISM.

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